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Acceleration and Motor Performance

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Experiments concerning the effects of acceleration on motor performance are discussed in a sequence which illustrates the evolution of research techniques in recent years. In the simplest of these techniques, performance is evaluated during or immediately following exposure to pre-programmed acceleration time histories. A more complex technique involves the study of interaction of subject performance with the pattern of acceleration experienced. Accelerations are actually controlled by subject performance by means of an analog computer control system. Certain limitations of centrifuge simulations are discussed.

INTRODUCTION

In spite of all of the technical developments of the last two decades, aircraft pilots continue to perform control functions very similar to those they were performing twenty years ago and with very similar instruments and controls. The pilot's job has become more demanding, however, and although his instruments are similar he now has many more of them to consider than in the past and these are arrayed before him in a cockpit which is, in many cases, more cramped than the cockpits of earlier aircraft. The pilot's task is further complicated in present-day aviation by pressure suits, G-suits, and other protective devices which he must wear. The penalty for any mistake in the pilot's overall pattern of performance has become much greater and there are fewer second chances once a mistake has been made. When it does become necessary for a pilot to part company with his aircraft in an emergency, he must be aided by some kind of ejection device. This device serves further to restrict available space and convenient design of the aircraft cockpit.

The simultaneous increase in both the restrictions and the demands imposed on military aviators has rendered a careful consideration of factors which may have been of less importance in the past of much greater concern in the present. Acceleration forces represent such a factor. In present-day conventional aircraft, the forces of acceleration encountered in turns and pulling out of dives may be five times or more the force of acceleration of the earth's gravitational field. The maximum accelerations encountered in aircraft have not increased appreciably over the last twenty years, but the duration of exposure to a given acceleration force in turns has increased with increased speed. The increased penalty for any kind of pilot error renders the effects of acceleration on performance of increased concern.

Actually, these justifications for a concern with acceleration seem almost trivial when compared with developments over the last five years in the realm of rockets and space flight. The accelerations involved in reaching the required velocity for orbital flight or escape from the vicinity of the earth will be high and prolonged compared with the accelerations of conventional aircraft, and equally high acceleration forces will be encountered in decelerating rocket vehicles for landing. In early manned space flight efforts it will be necessary to make full use of man's ability. Space and total mass in the early vehicles will be severely limited and the inclusion of equipment to perform functions which man could perform would represent unnecessary duplication. This is a sound logical argument but it must be supported by the actual demonstration of man's ability to perform satisfactorily during and following accelerations to which he may be exposed. For this reason studies of the effects of acceleration on performance have taken on increased importance in recent years. Most of these studies have been performed on centrifuges such as the Navy centrifuge illustrated in Fig. 1.

A summary of research on the effects of acceleration on human performance was published in 1956.[9] Since that time considerable

additional work has been accomplished in this area, particularly on complex motor performance such as that which may actually be required of pilots under various conditions of acceleration. Studies have ranged all the way from a consideration of the pilot's ability to perform those actions necessary for ejection while exposed to acceleration to rather complex situations in which the accelerations actually result from the pilot's own control manipulations, i.e. the interaction between performance and acceleration which occurs in actual flight is taken into account.

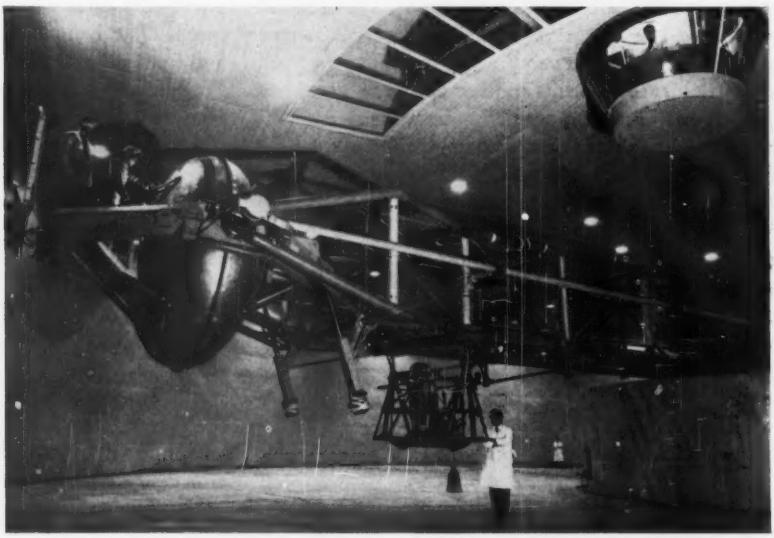

Fig. 1. The centrifuge at the Naval Air Development Center, Johnsville, Pa. The double gimbal mounting of the gondola permits continuous variation of the line of action of the resultant G force.

Many of these experiments have been reported in military technical reports or in journals which are not always readily available to all who may be interested in them. It therefore seems appropriate to summarize some of this work. The experiments reported here represent only a selected portion of all of the work which has been done. Nonetheless, the experiments included in this report are believed to provide a balanced picture of the kind of research which is being performed. The sequence in which these experiments are treated is not a strictly chronological one, rather it is one which follows the development of increasingly complex techniques which are being employed for experimental work in this area.

EJECTION

A number of studies has been conducted on the ability of pilots to go through the sequence of movements required for successful ejection.[12, 24] In an experiment conducted at Pensacola,[12] 5 out of 30 subjects, protected by anti-G-suits, failed to pull the ejection seat face-curtain (which initiates ejection) while under an acceleration of 2 G units in excess of their unprotected blackout level. The results of a series of experiments at the Naval Air Development Center,[21–24] clearly demonstrate that controls which may be adequate for a pilot wearing summer flying gear are wholly inadequate for a pilot wearing a full pressure suit, that the adequacy of a given control location may vary with the orientation of acceleration,

and that, in general, a control located on the front of the seat bucket can be actuated somewhat more quickly than a face-curtain control above the head.

This research was conducted under conditions of sustained acceleration at a fixed orientation. Subjects on the centrifuge were brought up to a given level of acceleration which was held and then given a signal to execute the ejection procedure. When the acceleration was positive, i.e. so oriented that it tended to pull the subject down into the seat, some subjects failed to complete the ejection procedure with a face-curtain at 5 or 6 G. When the acceleration tended to pull them forward out of the seat against restraining straps, almost all subjects were unable to pull the face-curtain at 6 G. Lateral acceleration and acceleration which forced the subject against the seat back did not cause as much difficulty. Some of the results of these experiments are presented in Fig. 2.

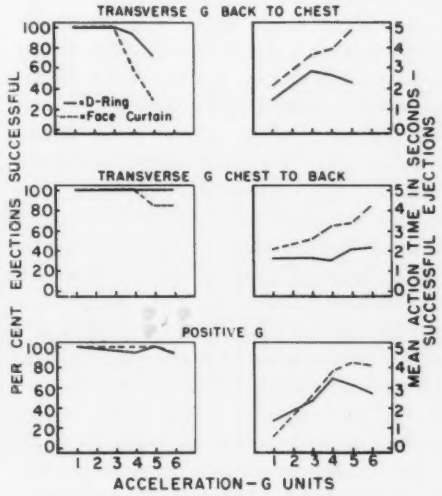

Fig. 2. Per cent of ejections successfully completed and the arithmetic means of the action times of these successful ejections for two controls during exposure to sustained acceleration forces in each of three orientations.

There are a variety of conditions of aircraft damage and uncontrolled flight which might result in relatively sustained acceleration forces on a pilot. There are other conditions, however, under which complex, fluctuating acceleration-force-patterns may be encountered.[14] Therefore, in addition to work with sustained accelerations, investigations of pilot ability to eject under conditions of fluctuating acceleration have been conducted on the centrifuge at the Naval Air Development Center.[22, 25, 26] The double gimbal mounting of the centrifuge gondola at the end of the rotating arm (See Fig. 1) affords three independently controllable motions of the centrifuge: the angular rotation of the centrifuge arm in a horizontal plane, tilting of the gondola through an angle of greater than 90° about the axis of the outer gimbal, and full rotation of the gondola through an angle of 360° about the inner gimbal axis which is perpendicular to the outer gimbal axis. By the combined control of these three dimensions of centrifuge motion, it is possible to vary the resultant linear acceleration force on a subject inside the gondola from 1 G when the centrifuge is stationary up to 40 G when the centrifuge is rotating at maximum rated angular velocity. At the same time it is possible to vary the orientation of the resultant G forces with respect to the subject inside the gondola by appropriate positioning of the gondola in its gimbal mounting.

Obviously, the motions of the centrifuge which are required to achieve a changing pattern of linear acceleration forces are quite unlike the motions through which an aircraft or spacecraft would go in producing the same pattern of linear accelerations. In order to duplicate aircraft or spacecraft flight accurately, it would be necessary to have independent control of the gondola along three orthogonal linear axes and about three orthogonal axes of rotation. The centrifuge can be used effectively to simulate selected components of the acceleration of aircraft or spacecraft, however. In most of the work on the Navy centrifuge an attempt has been made to simulate linear acceleration components accurately.

Patterns of linear acceleration employed in the study of ejection[22] varied in a manner and degree which were representative of forms of uncontrolled flight.[14] Times required for the various steps were carefully measured, and limitations of several standard ejection procedures were observed. In general, less difficulty was encountered with the fluctuating accelerations employed than with the higher level sustained accelerations.

PILOTING PERFORMANCE

Aircraft

There has been increasing concern in Naval Aviation about the effects of catapult accelerations on a pilot's ability to fly his aircraft immediately after launching. Aircraft that fly at higher speeds must leave the catapult at higher speeds, and this requires higher accelerations, since it is unlikely that longer catapults can be employed. Several experiments indicate that pilots can, in fact, sustain higher accelerations than those now employed without difficulty.[7, 15] Brown *et al.*[7] conducted an experiment to determine the possible effects of accelerations encountered during aircraft catapulting on a pilot's subsequent ability to fly his aircraft. An analysis of required performance indicated that the most critical task immediately after launching was control of the aircraft in pitch and roll. Pilots were therefore required to stabilize disturbances of an aircraft attitude indicator in pitch and roll immediately following exposure to transverse accelerations acting in the same direction as catapult accelerations. No decrement in performance was found even after exposure to accelerations of nearly 12 G.

Fletcher *et al.*[17] studied the effects of centrifuge acceleration on performance of a simulated air-to-air compensatory tracking task. During 141-sec runs subjects were exposed at different times to accelerations of up to 4 G. Acceleration exposures were of 10, 20 or 30 sec duration. It was found that tracking accuracy was better with shorter durations of exposure to acceleration and with lower levels of acceleration. Subjects performed significantly better with a right-hand, console control stick than they did with a conventional center stick.

Space Flight

The high accelerations anticipated under some conditions of space flight[1] have stimulated a variety of efforts to develop new methods of protection which will permit man to sustain these higher accelerations without physical injury or excessive discomfort. One of these methods consists of the use of a molded contour couch which provides a uniform distribution of support of the body. Recent evaluations of this method on the Navy centrifuge have demonstrated that transverse, chest-to-back accelerations as high as 25 G can be tolerated for a period of several seconds.[13] Under these conditions the subject was capable of manipulating a small right-hand joy stick control with the fingers in a plane normal to the line of action of the acceleration. Another method investigated consists of complete immersion of a subject. This provides uniform support of the body in any position. Under these conditions a subject, in water, has been able to withstand exposure to 31 transverse G with no restrictions on limb movement except those imposed by the bounds of the container.[19] Excessive mass and problems related to respiration impose limits on the use of this method in the near future, but it may ultimately be of practical importance.

Pilot performance during exposure to a pattern of acceleration similar to that which may be employed in a three-stage rocket has been investigated on the centrifuge at Wright Air Development Center.[27] Subjects were required to perform a compensatory tracking task in two dimensions. Separate indicators were provided for each dimension and a wrist-operated joy stick was used to effect control in both dimensions. The two indicators were both disturbed by a 0.087 c.p.s. sinusoidal input. Results for nine subjects suggest some

degradation of performance as a function of acceleration, but the results were not evaluated statistically. There is considerable interindividual variability. It is suggested that some of the performance decrement may result from illusory effects of angular acceleration which occurred on the centrifuge but which would not occur in a rocket. This study, which the authors point out is only preliminary, is of considerable importance in that it represents the first attempt to simulate a pattern of acceleration that may be encountered at some future time and then to evaluate the effects of exposure to this pattern on performance of a control task. This kind of experimentation, with continuing refinements of technique, has become of much greater importance with the approach of manned, rocket vehicles.

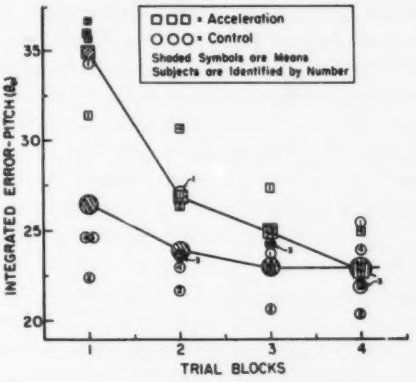

Fig. 3. Integrated error scores for control of a rocket vehicle attitude in pitch as a function of practice. Average error scores are presented for four successive trial blocks of three trials each. Performance during exposure to acceleration shows continuous improvement to the point where it is comparable with performance under control conditions.

The ability of pilots to control a rocket-propelled, orbital vehicle during the exit phase of its flight was recently studied on the Navy centrifuge.[3] Subject pilots were selected from among those pilots who may actually be required to fly the vehicle. It was found that pilots were able to perform relatively precise control motions during exposure to accelerations which simulated the thrust accelerations of the four-stage rocket vehicle. Of considerable importance was the finding that with repeated experience there is an improvement in performance under acceleration to the point where it is comparable to performance under control conditions at 1 G. This is illustrated in Fig. 3 by the decrease in average cumulative error over successive trial blocks. Performance was relatively stable under control conditions for all subjects except number 1, who had had no prior experience with the problem. His performance and rate of learning were nearly identical under acceleration and under control conditions. It would appear that under the circumstances of this experiment, there was very little transfer of training on a task practiced at 1 G to performance of the task under acceleration.

The loading of a right-hand control stick which was employed in this experiment was selected on the basis of pilot opinion prior to the experiment. After using the control stick during exposure to acceleration, all of the subject pilots agreed that a different load characteristic would be preferred. The solution to the problem of control load selection should

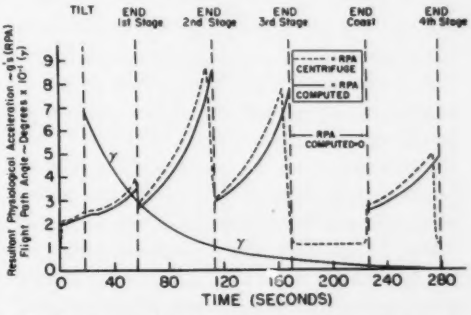

Fig. 4. An acceleration time history for a four-stage rocket vehicle. The centrifuge simulation is represented by a dashed line and illustrates the inability of the centrifuge to produce either instantaneous reductions in acceleration forces or resultant accelerations of less than 1 G.

not rest with pilot opinion, however. Experimental study of load characteristics in terms of their influence on an appropriate objective criterion of pilot performance should be conducted under a representative range of acceleration conditions.

Some of the limitations of centrifuge studies of acceleration may be clarified by further consideration of simulation of the four-stage rocket vehicle discussed in the preceding paragraph. An acceleration time history for such a vehicle is presented in Fig. 4 in the solid line graph. With decrease in vehicle mass and constant rocket thrust the acceleration builds up to a maximum at the termination of thrust and then falls abruptly to a lower level of acceleration provided by the next rocket stage. At the end of the third stage there is an interval during which no thrust is applied to the vehicle prior to firing of the fourth stage. If during this time the vehicle is in a ballistic trajectory, an occupant of the vehicle will be subjected to zero G. A simulation of this acceleration time history which can be accomplished on the centrifuge is presented by the dashed line in Fig. 4. It will be noted that after reaching a maximum level of acceleration it is not possible to reduce acceleration instantly. This would require an instantaneous stopping of the centrifuge arm to reduce centrifuge acceleration instantaneously to zero. Very abrupt stopping of the arm would result in an excessively high tangential component of acceleration and the resultant acceleration would rise to a high level prior to actual stopping of the centrifuge. This problem is overcome by a gradual reduction in centrifuge angular velocity such that at termination of the simulation of a given rocket stage, acceleration is reduced at a relatively fast but finite rate. It will be noted that during the predicted zero G phase in Fig. 4, the centrifuge simulation provides a resultant acceleration force of 1 G. This is a necessary result of the inability of the centrifuge to provide any sustained acceleration component which opposes the earth's gravity.

INTERACTION OF ACCELERATION AND PERFORMANCE

Vehicle Control

In all of the previously cited work on the effects of acceleration on complex tasks, the accelerations to which a subject was exposed were pre-programmed. The subject had no control over the acceleration, and changes in acceleration as a function of time were entirely predetermined by some type of programming device. This type of experimentation is somewhat unrealistic, since in many situations with the pilot in control of the vehicle the acceleration will vary from moment to moment in response to his control manipulations from moment to moment. At the same time, we may expect his control manipulations from moment to moment to be influenced by the changing pattern of acceleration. Pilot performance and acceleration will interact in some complex manner. The satisfactory study of this kind of situation cannot be accomplished in the laboratory unless such interaction is taken into account.[4]

Methods have been developed for studying the interaction of pilot performance and acceleration on the Navy centrifuge.[16, 20] The control system employed is illustrated schematically in Fig. 5. A subject in the gondola is provided with a control stick, rudder pedals, or any other types of control which may be required in the specific vehicle which is under investigation. A complete instrument panel simulation is also installed in the gondola. The subject manipulates his controls in an appropriate manner in response to information provided by the instrument panel. Control manipulations result in changing electrical signals which are transmitted to an analog computer simulation of the vehicle in question. A continuous real time solution of the flight problem is generated by the computer. The solution includes a complete description of vehicle motions in terms of changing acceleration components, changes in altitude, velocity, rate of climb or dive, heading and attitude.

Output signals which represent vehicle accelerations are converted by a co-ordinate conversion system into appropriate signals which control the centrifuge motions. In such a system the linear accelerations to which the pilot is exposed at any moment are appropriate for the immediately preceding control manipulations which he has performed. At the same time, other signals from the computer solution of the flight problem are used to control the instrument display on the panel in front of the pilot. Changes in altitude, speed and other variables are presented to the pilot on the panel in the appropriate sequence.

certain range of conditions during actual exposure to acceleration than comparable performance under control conditions at 1 G. This result has been confirmed in subsequent studies of space vehicle re-entry.[10] Apparently actual exposure to acceleration provides useful information to the pilot. The immediate information provided about the vehicle's condition of flight through sensory channels which are otherwise unutilized enables the pilot to do a better job in a complex control situation. Of course, acceleration conditions which markedly impair pilot performance are reached when direct mechanical effects on the pilot's limbs

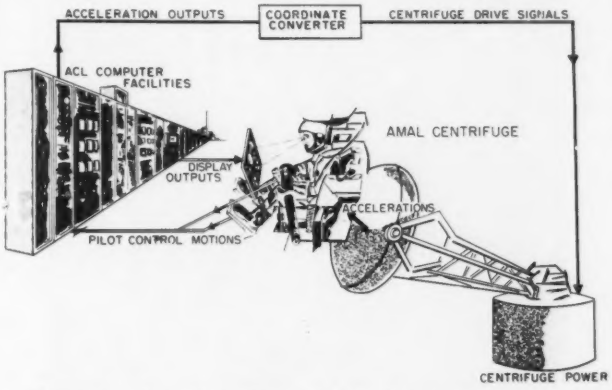

Fig. 5. A schematic illustration of a method of operating the Navy centrifuge which enables a subject pilot to control the actual acceleration forces to which he is exposed.

One of the first applications of this mode of centrifuge control was in the study of the X-15 research rocket vehicle.[11] The ability of pilots to control the vehicle during the difficult re-entry phase of the flight was studied under a variety of conditions of system failure. The results of this experiment were useful in that they demonstrated the feasibility of pilot control of the X-15 during re-entry even during exposure to fluctuating accelerations of a high level. Another aspect of the results was of considerable interest. It was found that pilot performance with respect to the ability to damp out unwanted oscillations and hold acceleration to a minimum was slightly better within a

reduce the efficiency of his control performance When the levels of acceleration are sufficiently high or the fluctuations sufficiently violent, this kind of effect completely offsets any advantage of acceleration. It may be concluded that when accelerations are not excessive pilot performance may be improved by actual exposure.

Tracking

The study of tracking problems with the subject in control of the centrifuge presents a situation which is slightly more complex than that dealt with in the preceding paragraph. Such a situation exists when the task performed

by the man does not merely require control of his own vehicle, but also requires that he follow some external, continuously varying reference. Such a requirement exists in an air-to-air attack where the pilot of one vehicle flies with reference to a second vehicle which may be performing evasive maneuvers. In this kind of situation the information provided by the acceleration forces and motions of the pilot's own vehicle is not immediately related to the primary task, i.e. pursuit of the external vehicle. Acceleration forces are useful for improving the smoothness and co-ordination of control of the pilot's own vehicle, but smooth control and optimum tracking do not always go hand-in-hand.

A centrifuge installation for the study of a problem of this type is illustrated in Fig. 6. The pilot is required to fly the centrifuge analog of a specific aircraft with reference to a signal presented to him on a cathode ray oscilloscope mounted above the instrument panel. The command signal on the scope varies in a random fashion which cannot be anticipated by the pilot. Under these conditions we find that performance of the tracking task is impaired by exposure to acceleration. The results of an experiment of this kind[6] are

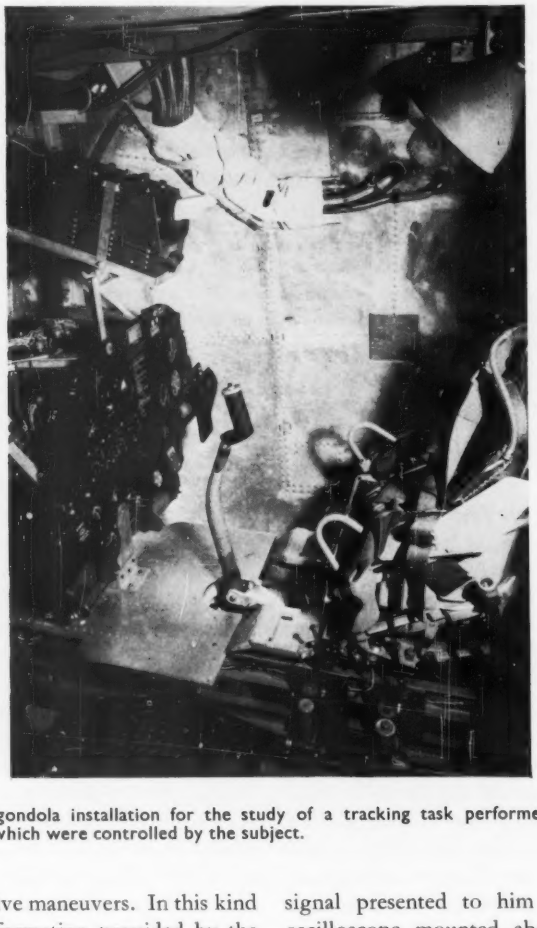

Fig. 6. A centrifuge gondola installation for the study of a tracking task performed during exposure to accelerations which were controlled by the subject.

illustrated in Fig. 7. Three histograms are presented which represent cumulative error scores for the vertical dimension of tracking, the horizontal dimension of tracking and a measure of vehicle co-ordination. Scores are given both for experimental conditions under

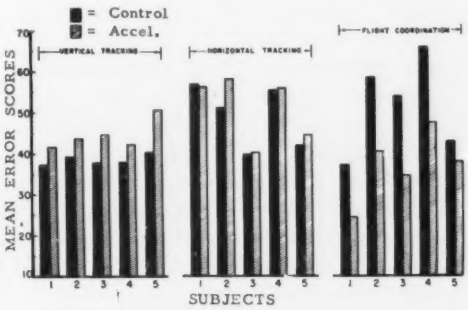

Fig. 7. Average error scores for vertical tracking, horizontal tracking and flight co-ordination in an experiment in which the subject controlled accelerations. It is evident that each of the five subjects shows a decrement in vertical tracking ability and an improvement in flight co-ordination during exposure to acceleration as compared with his performance under control conditions at 1 G.

acceleration and for control conditions at 1 G. It is evident that the vertical tracking performance is better under control conditions than it is under acceleration. On the other hand, vehicle co-ordination is significantly better under acceleration than it is under control conditions. The requirement for additional attention to vehicle co-ordination which is imposed on the pilot by the fluctuating acceleration pattern would appear to be met at the expense of some other aspect of his performance, in this case, tracking performance.

In all centrifuge studies of performance it is important to recognize the facts mentioned earlier, namely that angular accelerations on a centrifuge may be highly unrealistic even though linear accelerations represent an accurate reproduction of what may be encountered in aircraft. Early centrifuge work of the kind discussed in the preceding paragraph indicated that pilots find more difficulty in operating the centrifuge simulations than do non-pilots.[2] Apparently, anomalous angular accelerations cause the pilots considerable difficulty when evaluated in the light of prior pilot experience in aircraft. Lacking this experience, the non-pilot has little difficulty. In a recent study in which tracking performance on the centrifuge was compared with tracking performance in an aircraft,[8] it was found that the subject, a non-pilot, who had most experience on the centrifuge performed most proficiently on the centrifuge but poorest in the aircraft. Pilots did very well in the aircraft, even better than performance under control conditions in many cases, but performed relatively poorly on the centrifuge. Some of the results of this experiment are presented in Fig. 8. Average integrated tracking error in roll is given for three test pilots, a Navy pilot, and two non-pilots, under control conditions (Static), two conditions of centrifuge simulation (Dynamic I and II), and in the aircraft.

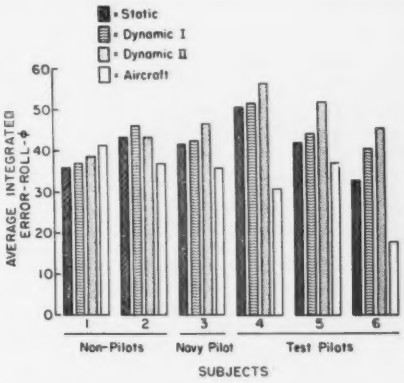

Fig. 8. Average integrated error in the "roll" dimension of a tracking task for each of four experimental conditions: a static simulator, two types of centrifuge simulation (Dynamic I, and II), and in the aircraft which had been simulated.

There is a striking similarity among the profiles for the three test pilots.

There is at least a possibility of negative transfer between performance training on a centrifuge and in an aircraft. However, if this is

the case, it probably applies only to the tracking problem situation, and then, only for conventional aircraft in which linear accelerations are relatively low and angular accelerations are prominent. Pilots report that anomalous angular accelerations do not seem to be as disturbing when linear accelerations are high (4 G or more) as when they are low (1–3 G). In support of this position, results of an experiment by Gray and Crosbie[18] may be cited. Linear accelerations were increased in steps with angular acceleration held constant. It was found that the duration of the oculogyral illusion (a response to angular acceleration) decreased as linear acceleration was increased.

PSYCHOLOGICAL FACTORS

It has been suggested (not entirely seriously) that all our experimental efforts may be of little consequence. It is argued that the anxieties which will be induced by the prospect of an actual space flight will be of much greater importance than such things as acceleration. We know of no practical way to produce these anxieties in the laboratory when a space flight is not actually impending. However, it can be demonstrated that the anticipation of acceleration forces may at least contribute to these anxieties. Pulse rates prior to exposure and during exposure to simulated catapult acceleration[7] are plotted as a function of acceleration level in Fig. 9. The increase in pre-acceleration pulse rate at the higher acceleration levels is highly significant. These results demonstrate that after having had some experience with exposure to acceleration at various levels, a subject's heart rate will vary prior to a centrifuge run when he is told what the level of acceleration is to be. If we accept an elevated heart rate as an index of anxiety, then it would appear that the prospect of a centrifuge ride may be a pretty good anxiety inducer. This provides an additional justification for centrifuge experimentation beyond the fact that there is no other practical method for the experimental study of the effects of acceleration on pilot performance.

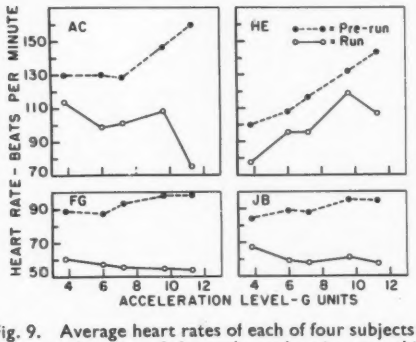

Fig. 9. Average heart rates of each of four subjects as a function of the peak accelerations to which subjects were exposed during a study of catapult launching. Heart rates were measured both prior to and during exposure. Subjects were informed as to the acceleration level to be achieved in advance of each run.

CONCLUSION

The centrifuge has become an essential tool for the study of vehicle control problems in certain aircraft of marginal stability and in rocket vehicles which will subject their occupants to high linear acceleration forces.[5] For example, it has been possible to demonstrate that under certain conditions the accelerations which result from pilot control manipulations may be associated with improved performance. In addition, results of experiments suggest that the design of controls can be materially improved when effects of acceleration are evaluated. Disadvantages associated with anomalous angular accelerations must be taken into account, but, in general, they appear to be outweighed by the advantages of centrifuge research. In recent years, a number of experiments have been performed which provide valuable information concerning the role which man will play in our space program and more experiments of this kind are planned for the future.

Acknowledgement

All Figures are from official photographs of the U.S. Navy.

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PREVIEW: IT'S ALL OVER IN ONE SECOND. . . . . .

Time after contact (seconds) 1/40 1/25 1/15 1/11

Automobile Collisions on Purpose

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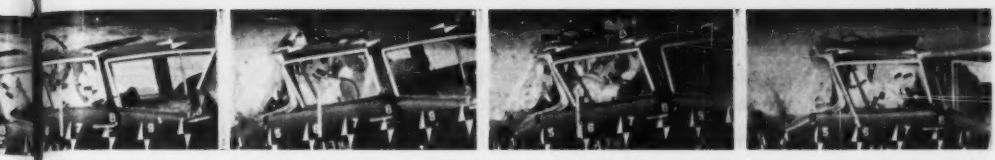
This paper presents a brief discussion of some of the findings from forty-eight full-scale automobile collision experiments conducted at UCLA during the past ten years. These experiments have provided critically needed data on physical factors relating to vehicular collision dynamics and attending motorist injuries. Use of both human subjects and anthropometric dummies facilitate procurement of critically needed data on the relation of design to injury causation.

Specific data derived from these experiments include deceleration patterns for different locations on the motorist and car structure, the relation of impact speed to car deformation and repair costs, the performance of motorist restraining devices and the interaction of human and dummy motorists with their cars' interior and external environment during collisions.

INTRODUCTION

No greater duration than one-quarter of a second is required for two well-engineered automobiles approaching one another at 50 mph to be converted into junk. Driver reaction time—the time required to perceive, interpret and commence to react to an environmental disturbance—averages ¾ sec. Should a head-on collision between cars traveling 50 mph appear imminent when the cars are still 100 ft apart, no preventive effort could be initiated before they crashed. The ensuing quarter-second of destruction embroils the motorists within collapsing structures with injurious forces having a magnitude measured in tons rather than pounds. Even if there were sufficient time to brace himself, these forces completely overwhelm the motorist.

Not all collisions are this violent even though most of them produce overwhelming force systems. The current rate of 1.4 million motorists injured each year provides an exposure to injury that could include more than one member of every family sometime during their lifetime. What are the measures which will improve this situation? Accident prevention measures will always play a prominent role, but accident prevention alone is not sufficient. Vehicle collisions whether on land, in the air or at sea, are a part of the price we pay for transportation. Each system of transportation involves many dependent variable factors and these vehicle-associated factors operate under enviromental conditions having other independent and to a large extent, uncontrollable variables. Consequently, the multivariant nature of any transportation system makes accidents an unwanted, regrettable, but nevertheless, a not completely irrepressible by-product. A supplement to *Accident Prevention* should, therefore, be *Injury Minimization.* Research serves to guide the engineer in revision of vehicles which consequently leads to reduction in transportation injuries. Research, for this purpose, may take the form of developing better energy-absorbent materials such as the low density solid plastics and the deformable rubber-like materials that return slowly to their original configurations after the deforming forces are removed. On, research



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may include analysis of data recorded at the scenes of accidents that lead to certain conclusions concerning injury producing factors within the car.

A highly controversial approach to collision research was initiated at the Institute of Transportation and Traffic Engineering (I.T.T.E.), University of California, in 1950. Full-scale automobiles were instrumented and deliberately crashed under controlled conditions for the purpose of collecting engineering and medico-engineering data. Under the encouragement and guidance of Professor J. H. Mathewson, Assistant Director of I.T.T.E., the collision research project developed from experiments that used 25-dollar junker-autos and laboratory modified mannequin drivers to experiments that cost $10,000 and use new cars and highly engineered anthropometric dummies.

Ten thousand dollars per experimental collision seems a premium price for research. Consider for a moment, however, the price we're paying for automobile accidents. The five billion dollars paid by the motoring public last year for accidents, while a staggering amount, is trivial by comparison to the loss of life and the suffering of the injured and their loved ones. This five billion dollars bought nothing—not even an opportunity for a reduction of motorist injuries in future years. Ten years of intensive research by I.T.T.E.'s Automobile Collision Injury Research Project, utilizing but one ten-thousandth of this annual dollars loss, has provided findings pointing to improvement in the motorist collision injury problem.

Automobile collisions are double impact events. The first impact involves the vehicle striking another object. The second impact results when the motorist involuntarily reacts

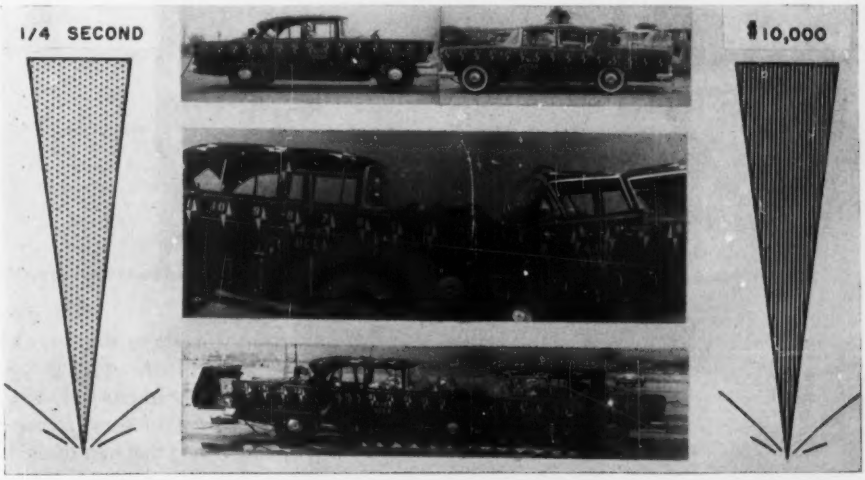


Fig. 1. Too expensive to permit an error, these vital experiments must be precise and comprehensive.

to the first impact and strikes the car's interior, or is thrown outside the car. The consequences of the first (vehicle) impact depends on such factors as speed, mass and structural properties of the vehicle as well as the point of impact, impact eccentricity and type of object struck, together with associated factors such as subsequent or even tertiary impacts and, in some cases, post-collision factors such as fire or water immersion.

Additionally, inside the car, still another group of factors complicate the motorist survival problem. Deceleration forces prevail like those experienced in a severe fall. The surfaces encountered by the motorist within the car may be relatively non-yielding so that they may produce puncture wounds or they may allow excessive bending and shearing forces to develop—forces that cause internal injuries. The injury-producing aspects of these forces may be reduced by controlling that part of the body on which the collision deceleration forces are

Fig. 2. Experimental collisions are devised to precisely duplicate physical factors involved in automobile accidents.

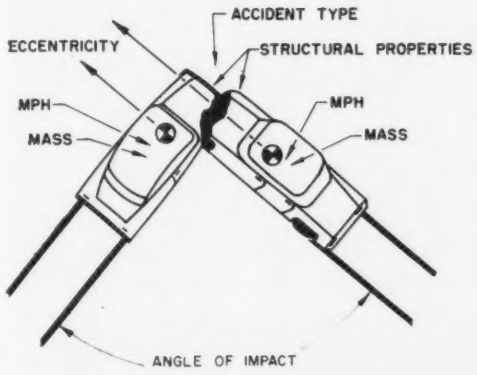


Fig. 3. Accidents involve complicated phenomena.

concentrated. The automobile lap-type belt effectively provides this control for minor to moderately-severe collisions. In more serious accidents, collision forces reach levels which challenge survival—even with an effective motorist restraining device. For the majority of accidents, however, it has been experimentally determined that a lap belt provides effective motorist collision protection over a wide-range of loadings. Actual accident experience where seat belts were in use, amplify these experimental findings.

HOW ARE EXPERIMENTAL COLLISIONS CONDUCTED?

Notwithstanding six years of previous experience in conducting experimental automobile collisions, the first fully-instrumented head-on collision required more than a year of

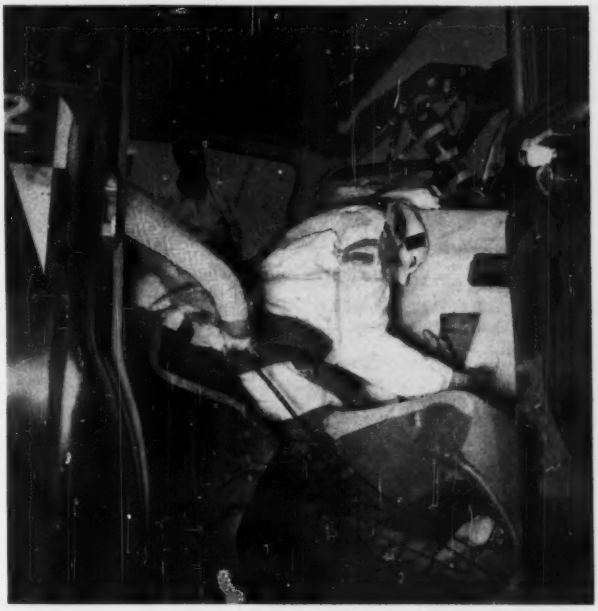


Fig. 4. Motorist seat-belt forces ranging to 7 tons were measured in the 50 mph head-on. (*Note*: Floor-pan torn out near belt-anchorage.)

engineering planning, training of personnel, procurement, fabrication, installation and evaluation of equipment and facilities by the I.T.T.E. project staff. This task was considerably accelerated by the energetic and proficient work of the assistant project engineer, Arnold W. Siegel.

In rapidly-expanding California, I.T.T.E. was informed that there was no such thing as an abandoned road suitable for a test site. Aerial surveys conducted 200 miles north, 100 miles south, and eastward from Los Angeles to the Arizona border failed to locate a suitable test site. Repeatedly, rerouted sections of old highways, former airports, etc., were appraised as being unsuitable. Finally, clearance was given by the U.S. Navy to conduct experiments on its airfield at Terminal Island. The 3000-ft paved and level surface was ideal. In developing a satisfactory low-cost ground-anchored monorail guide system for directionally controlling the collision vehicles, there were, however, several seemingly impossible problems to surmount. One end of the field was terminated by a sea wall at the Pacific Ocean. The intense salt atmosphere generated by the pounding waves would be extremely corrosive to the monorail, whether steel or aluminum. The hot summer sun and cool foggy evenings would produce extreme temperature variations causing the track to extend and shorten considerably. It was not possible to bond the track by adhesives, or to mechanically fasten the track by expansion lugs or missile-nails because of the characteristic cold-flow properties of asphalt surfaces. Thirty-two-hundred feet of aluminum rail designed to I.T.T.E.'s specifications were extruded by Reynolds Metals Corp. A test section installation was heat-cycled, using intermittent applications of burning alcohol and crushed ice to duplicate summer and winter exposure

Fig. 5. Crash car is paced by instrument recording car.

extremes. It was found that a $\frac{3}{16}$-in. gap between 30-ft lengths of track was adequate allowance for track expansion. Twelve-in. spikes, used to secure the track to the asphalt surface, continued to effectively anchor the track during these heat expansion tests. The highly corrosive sea atmosphere made it necessary to anodize the track, and the connecting base plates and anchor spikes were protected by cadmium plating.

Operational techniques had to be devised that would permit two cars to approach each other at closing speeds in excess of 100 mph to impact within 6 in. of a predesignated point, and to be steered within 2 in. of the prescribed alignment for impact. In addition, the car speeds were to be identical and within 2 mph of the predesignated speed. Furthermore, during impact, both cars were to be free of speed and directional constraining influences.

To accomplish this, one of the cars was designated the *power car* and was provided with a governor to maintain a pre-set speed as the cars approached each other. Extending from the rear of the power car, a $\frac{3}{8}$-in. steel cable passed through a sheave anchored to the asphalt surface and back under the power car to the front-end of the opposing crash car, positioned at the opposite end of the 2800-ft track. When properly adjusted, this system compelled the cars to impact at the prescribed point and further served to equalize their approach speeds.

The cars were guided along the monorail by a phenolic shoe which slid along inside the U-shaped guide rail. This shoe was fastened by a yoke extending from the shoe to the front bumper. The tow cable was released a fraction of a sec before impact by a disconnector hook. The track in both directions terminated 20 ft from the impact point to eliminate constraining influence during collision. These collision experiments are conducted at speeds measured with an accuracy of $\frac{1}{10}$ mph.

Fig. 6. Head-on collision at 53 mph brings windshields within a foot of touching each other.

Each crash car was flanked by a man-driven recording car carrying a 20-channel oscillograph and accessory equipment. The only physical connection between the recording and crash cars was an electric cable leading from the crash car sensing units to the recording oscillographs. This cable also carried channels for remote control of the crash car brakes, cameras and subordinate instrumentation

systems. An opened steel drum mounted on the recording car's rear fender stored the bulk of the 100-ft electric cable until it was paid out during the last few seconds before impact. The shaded side of the car was effectively illuminated by a sequentially-fired multi-flash bulb unit.

Deceleration rates for the undeformed rearward portions of the car varied from 45 to 55 G. To understand the significance of deceleration rates of this magnitude, consider the effect of a car deceleration at 50 G on a rear seat occupant weighing 170 lb. If such an occupant could be held in place during a 50 G crash by a restraining device, a device considerably more effective than say, a lap belt, his weight would actually increase during impact to 170 lb times 50, or to 8500 lb. Actually, the dummy weight was nearly double this value (15,000 lb) during the crash shown in Fig. 6, as measured by seat-belt tensiometers The difference between the ideally-constituted and the practical restraining device performances results from slackness and is to a large extent inherent in all restraining systems. Additional information is available on the relation "slack" bears to restraining loads applied to subjects during collision.[7]

For this series of head-on collision experiments, the cars were crashed with a one-ft offset from a center into center head-on position. This arrangement duplicated a more commonly occurring situation and provided data on the affect of an offset on collision dynamics. The rear ends of the cars rotated 8 ft counter clockwise as a result of this one-ft offset. Their positions of rest and their rather close proximity to the instrument recording cars are shown in Fig. 7.

Post-collision observations which are of interest to enforcement organizations such as

Fig. 7. High speed cameras are located at ground levels and tower positions. Data recording continues immediately following the collision.

highway patrols, include relative positions and types of debris, pavement gouges and brush skid marks. Furthermore, photographic and engineering data from experimental collisions conducted at known velocities provide calibrated references for speed judgments of accident collisions by investigating officers.

SOME FACTS ABOUT HEAD-ON COLLISIONS

It is generally conceded that styling rather than engineering sells the automobile, although this does not mean that a reputation for good engineering is not an essential ingredient in automotive sales. The motoring public is content to dismiss engineering considerations with an assumption that all cars are well-engineered so that they may simplify selection to an evaluation of styling preferences within their budget. The car body forms a pleasing envelope over the functional structured components. Recent trends toward elaborate rear fender designs, sometimes involving combinations of convex and concave surfaces, appeal to many, even though they increase the cost of the car. Most of us experience a bent or crushed fender sooner or later. Complicated fender designs may cost more than double the amount required to repair comparable damage to the simpler configurations. When involved in collisions considerably more severe than the "fender-bender" variety, these repair cost differences are not as apparent or important. In a series of five head-on collision experiments involving four makes of ten new cars, an approximate linear relationship was found to exist between impact velocity and repair costs.

Fig. 8. Collision research provides accident investigators with the first known impact speed vs. car deformation data.

This is particularly impressive when we consider that the kinetic energy or energy of motion of the car varies as the square of velocity.

A low-priced American car crashing head-on at 40 mph costs about $1900 to repair, and at one-quarter the impact energy for 20 mph, the repair bill would be $900. This condition may be explained by considering the extent of permanent front-end deformation. For the 40 mph collision, 1.7 ft deformation or caving-in of the front-end occurs in contrast to 1.2 ft

for 20 mph. Obviously, the collapsibility of the front-end structure of a car is not uniform. Progressive increases in front-end deformation are repulsed by more than proportionate increases in resistive force as the more substantial structures, the main frame, front-wheel assembly and engine are encountered directly. New "low-priced" U.S. cars will be totaled-out by head-on collisions around 40 mph, that is, repair costs equal or exceed new car costs for the 40 mph head-on. Such collisions are generally, though not necessarily, fatal. Automotive manufacturers are taking steps to improve car interiors in order to reduce collision injuries. The padded dashboard is one step in the right direction; eventual elimination of the protruding dash will be a further improvement. The steering wheel is a device used by the driver for guiding a vehicle, but on encountering a front-end impact the steering wheel turns on the driver and becomes an injury—or lethal-dealing instrument. A well-padded large-surfaced steering wheel hub and collapsible splined steering column would greatly reduce driver collision injuries. Also, a driver wearing lap and shoulder safety belts would be restrained from impact with the steering wheel. For collisions appreciably above 20 mph, however, the steering column extension towards the driver may be sufficient to injure or kill even the restrained motorist.

In six head-on collisions at speeds ranging from 21 to 53 mph, the front seat compartment, with one exception, remained intact. This is to say, the volume and general configuration of this compartment was not appreciably altered during these head-on crashes. The exception occurred in one of the two cars crashing at 53 mph. In that collision, the driver's compartment area was collapsed sufficiently to preclude any possibility for driver survival. In the other head-on collisions the front-ends were damaged or demolished, but the body structure around the motorist remained intact. For the head-on impact speed and peak deceleration of the motorist compartment, a parallel to the approximate proportional relation between impact speed and repair costs was found to exist. The 21 mph impact was attended by a peak deceleration of 20 G, the 27 mph head-on registered a peak of 30 G, and the 50 mph showed approximately 50 G.

Deceleration rates to 50 G are known to be within the survivable range, at least for some individuals, providing a well-designed restraining harness is in use. A man-size dummy wearing an Air-Force-type lap belt which had a rated strength of 8000 lb, sheared the an-

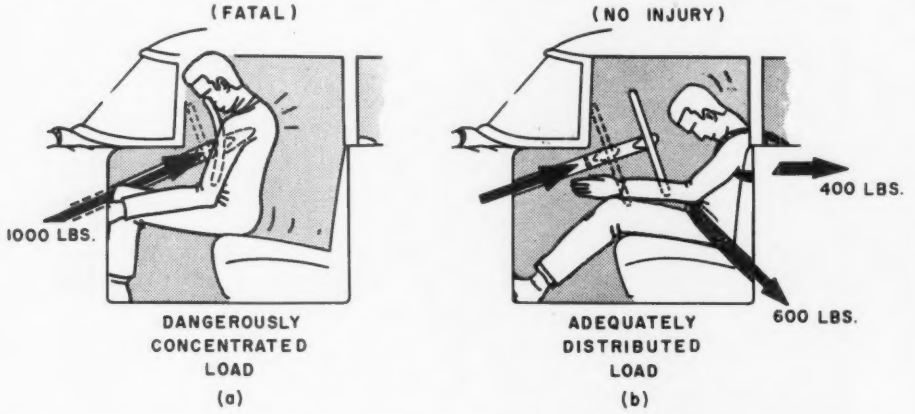


Fig. 9. Front-end impacts may thrust steering column into driver. A chest restraining device reduces this hazard.

chorage during a 47 mph head-on collision when belt load readings reached 9000 lb. It is a continuing problem to provide an effective restraining device for motorists which does not represent discomfort and inconvenience. Until a better performing device is developed that is acceptable for the motoring public, lap-type safety belts like those used in passenger aircraft are the best safety devices motorists can buy.

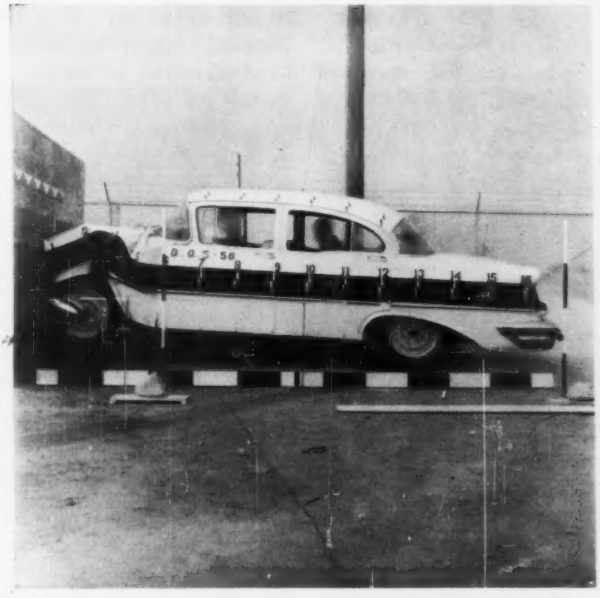


Fig. 10. Striking a fixed object at 23 mph produces serious to fatal motorist injuries.

THE FIXED OBJECT HAZARD

Driving the modern automobile over our too prevalent 30- to 40-year-old rural road systems presents hazards similar to the problem which would be encountered by the modern streamlined diesel passenger train attempting to negotiate a trolley line. The modern car is wider, lower and considerably more powerful than the 1920 vintage. When these vintage road systems were first designed, no allowance was made for cars running off the road. These roads were adequate for the speeds at which the older cars could perform. Today, as many motorists are killed by their vehicles running off the road as are killed by colliding with other vehicles. Isolated fixed objects such as trees, utility poles, and abutments bordering vintage road systems present the continuous threat of instant death to motorists. A moment's inattentiveness, a blowout, or crowding by oncoming or passing traffic are circumstances leading to dangerous collisions with isolated objects.

These isolated fixed objects are not to be confused with protective structures like the guard rails found on curves and the continuous structure separating opposing lanes of high-speed traffic. Such protective fixed objects serve as deflectors for cars out of control to reduce the probability of more serious collision involvement.

A fixed object impact may be more dangerous than a head-on collision. Experimental collisions involving vehicles striking a wall at 25 mph produced passenger compartment decelerations in the 30 to 40 G range.[6] Head-on

collisions at comparable speeds did not exceed 30 G, even though both cars were approaching one another at a closing speed of 50 mph. This seeming paradox is better understood if we consider the fact that each car has to change its velocity from 25 to zero mph during the crash, not from 50 mph to zero, and furthermore that each of the opposing cars are collapsible structures capable of moderating the decelaration rate of the passenger compartment through the energy absorbing collapse-action of their respective front-end structures. Intermeshing of the two colliding structures further extends the deceleration distance with a corresponding reduction in peak deceleration. A car striking a fixed barrier may not penetrate the barrier significantly so that the collapse action of the front-end must account for all passenger-compartment force reduction.

Well-designed highways have liberal shoulders and wide median strips free of fixed hazards. To the motorist jumping a narrow painted divider strip or low curb separating on-coming traffic, the opposing traffic may be as deadly as the menace of fixed hazards. Where land values prevent the use of a liberal median strip, an appropriately designed protective barrier separating opposing traffic should be provided.[1, 5] Night-driving fatigue and temporary night blindness would be reduced if this protective barrier were designed to eliminate headlight glare as well. Such provisions are being made on some of our modern highway systems, but are a regrettable oversight on most of our more congested highways.

THE REAR-END COLLISION

Not all menaces to motorists are as difficult to correct as removal of fixed hazards adjacent to roadways and physical separation of opposing traffic lanes. For example, the solution to injuries often attending the frequently occurring rear-end collision is simple. Technological advances in automotive transportation may be expected to foster problems which must be solved before full advantage of general system improvements may be realized. During the past decade, the motorist has seen the freeway, parkway, expressway and turnpike make their début and become recognized as the modern highway system. Congestion on these super highways has fostered a menace which carries an ominous penalty, a double jeopardy which succeeds in trapping the best of drivers. During congestion, traffic can crawl below 10 mph and maintain an interval between cars sufficient to permit panic stops without likelihood of impact to the car in front or subsequently by the car to the rear, providing everyone remains attentive. Above 10 mph, car intervals must be increased more than a proportional amount to maintain safe stopping distances.

To increase the gap more than one car length plus a very small squeeze factor invites lane changing which of itself is hazardous, especially during traffic congestion. To prevent lane changing and the impatience with which drivers react, under congestion, to cars ahead maintaining larger intervals, drivers have assumed the practice of maintaining intervals too short for safe driving. Masses of vehicles travel the modern highway "cocked" for collision. Almost any minor event such as a change in lane by a single car can trigger one or a series of rear-end collisions by forcing subsequent cars to brake their speeds at progressively greater rates to avert collision. This wave of increased stopping progresses rearward until it reaches the "panic stop" rate. This instigator car and the cars to the rear of it, and frequently other cars following these are involved in ensuing rear-end collisions. On freeways, rear-end collisions result more often from inability to stop in the maintained interval than from gross inattentiveness. Unfortunately, "driving ahead" under these conditions provides no assurance that anticipation of difficulty will prevent the first or second car behind from inducing a rear-end collision, which may affect cars ahead as well as a considerable number of cars to the rear. Thus, without

discrimination, the good and the poor driver share this rear-end injury hazard.

The solution to the problem of reducing the frequency of rear-end collisions has not been found. If more highways could be built at a rate which exceeded increases in motor vehicle usage, congestion would be reduced. Possibly a car-interval guard would be of value, such as a speed-dependent electronic interval guard that flashes an amber light at anyone following too closely; or, equipment like RCA's "Flying Tail"[3] which would convey information on headway and the speed of the car ahead; and G.M.'s automatic car guidance system,[2] representing a similar solution to the problem. Regardless of the eventual solution, the injury problem generated by rear-end collisions can, for the most part, be eliminated, as will be illustrated.

At I.T.T.E., two series of rear-end collision experiments have been conducted.[6, 8] Standard-size American passenger automobiles were used and both human and anthropometric dummies served as motorists. The humans took advantage of their mechanical counterparts by placing them in the more hazardous exposures. These collision studies typified the rear-end collision occurring when a vehicle has stopped on the freeway or at a traffic signal. The front car was stationary at the instant of impact by the rear car, which was traveling at speeds from 7 to 23 mph. The statement that things are not always what they seem was never better illustrated than in its application to the rear-end collision.

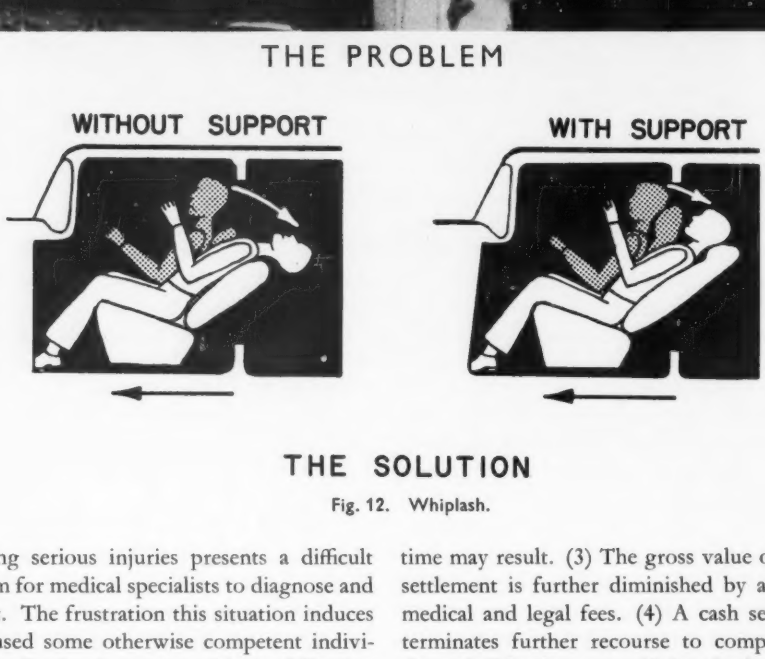
A series of paradoxes were identified in these studies. For example, the car struck from behind accelerates at rates comparable to the deceleration rates of the striking car but the struck car generally receives little damage as compared to the striking car. More important is what happens to the motorist. Injuries from most rear-end collisions are bloodless. When blood is spilled, it is most frequently the nose or face of the occupant of the striking car. Fortunately, these generally superficial injuries heal rapidly with no residual complaints. The all-too-often seriously injured party, the motorist of the lightly damaged struck car may not be aware of his injuries, injuries which were sustained during impact when his head was violently snapped rearward. It may be several hours or longer before pain in the neck and back suggests injury. Pain may be sustained

Fig. 11. Impact with stationary vehicle.

or recurrent and physical impairment may range from reduced physical activity to the extreme of crippling inactivity or death.

These head-snapping or "whiplash" injuries are unexpected; the recipient is struck from behind. The often subtle nature of attending serious injuries presents a difficult problem for medical specialists to diagnose and to treat. The frustration this situation induces has caused some otherwise competent individuals to dismiss the matter with the following statement: "Whiplash injuries are quickly cured by application of a greenback poultice". The inference being that the whiplash victim is malingering until a cash settlement is awarded. In addition to contributing malicious insult to an injured party this statement avoids certain basic facts. (1) Whiplash injuries are unsolicited. (2) Considerable pain and attending reduced physical activity for a long period of time may result. (3) The gross value of a cash settlement is further diminished by attendant medical and legal fees. (4) A cash settlement terminates further recourse to compensation through litigation, even if the physical condition of the injured further deteriorates so that seeking post-settlement legal assistance is worthless. Furthermore, by the time a settle-

THE PROBLEM



THE SOLUTION

Fig. 12. Whiplash.

ment is reached the attending doctor has generally done all within his power to help the patient. The patient consequently chooses to live with his residual impairment without calling additional attention to the matter, which has been hastily and irresponsibly dismissed as a "green-back poultice" cure.

The experiments conducted at I.T.T.E. showed that injury producing acceleration forces can prevail at impact speeds as low as 7 mph. With respect to the cause of the injury, the magnitude of force is subordinate to the manner in which the force is applied to the motorist. A 50-lb force applied to one part of the body may produce serious injury, even though 100 times that force applied differently, had previously been sustained without significant injury. In the rear-end collision, whiplash results from the struck car being accelerated forward. The car-seat back presses firmly against the passenger's back accelerating the upper half of his body—with the exception of his head. The head is left "behind" during this acceleration, thereby placing the neck in an extremely extended and flexed condition. This neck bending force extends down the spine frequently leading to spinal injury at a level where the seat back was providing adequate back support. If the adult passenger's 10 to 12-lb head had been similarly supported, no injury would have resulted.

The forces developed during whiplash are high, considering the leverage through which they operate. The center of an adult's head ranges from 12 to 20 in. above his back support. Furthermore, the rearward direction in which the head is forced is the direction most likely to bring about injury. Forward movement of the head is checked by the chin protrusion, sideways movement by the shoulders. No comparable natural protection exists for rearward head movements.

Consider one of UCLA's experiments that involved an anthropometric dummy seated behind the wheel in a stationary car struck by another car traveling 23 mph. A driver's head (rotational-component) load of 308 lb was measured, synchronized with an 84-lb (translation) load. The resultant 320 lb acted through the center of mass of the head with a mechanical advantage substantially greater than would be implied by the 18-in. bending moment from the center of mass of the head down to the top of the seat back.

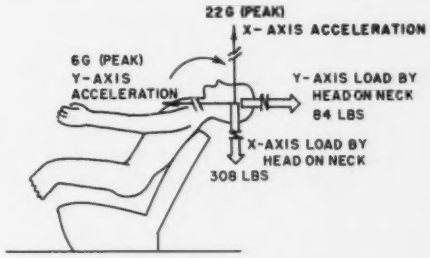


Fig. 13. Motorist's head acceleration and force vectors during a rear-end collision experiment; striking speed, 23 mph.

The inertia effect of the lower limbs tend to pin the hips against the seat back; the center of pressure of the seat-back during collision acceleration is situated above mid-back; the mass of the arms and shoulder girdle augment the inertia effect of the head. During impact, the torso slides up the inclined seat back and rotates rearward, as illustrated by

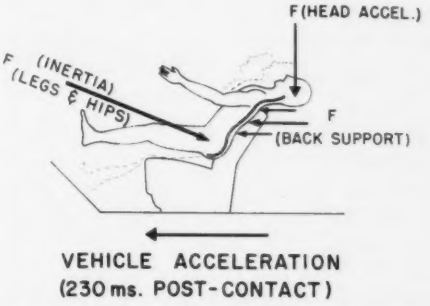


Fig. 14. Motorist's force vectors during a rear-end collision.

Figs. 13 and 14. Under these conditions, the low seat-back of present-day cars unlike many of its older predecessors, cannot distribute support throughout the back but instead acts as a fulcrum.

The forces acting on the vertebral column are shown schematically in simplified form in Fig. 15. The inertia force of the legs and hips, F_i, acting through the hip-girdle, may be resolved into the transverse component, F_i', and its corresponding vertebral compressive component; the forces of the fulcrum-like back-support, $F_{b.s.}$ are shown with distribution limited to the upper mid-back; the inertia forces from head acceleration, $F_{h.a.}$, may be resolved into a transverse component, $F_{h.a.}'$

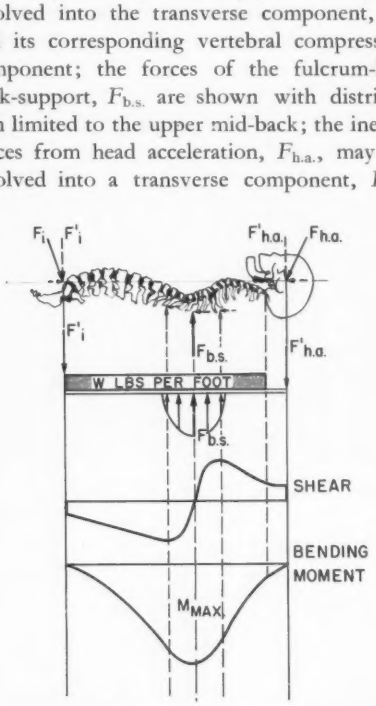


Fig. 15. Analysis of patterns of stresses to which the vertebral column is subjected during a rear-end collision.

and its corresponding vertebral compressive component. A small downward (frictional) component exerted by the seatback produces an additional compressive loading to the vertebral column. The force components of the head, seat-back and lower limbs constituting vertebral compressive forces predispose the vertebral column to buckling. The normal "S" curvature of the spine makes it even less able to sustain compressive loadings than would be true if the spine were naturally straight. The aggravation of injury by these factors will, however, be neglected in the interest of brevity.

Assume the torso to weigh W lb per ft, uniformly distributed along its spinal axis. Assume further that this spinal axis is a simple beam, supported by the fulcrum action of the back support force, $F_{b.s.}$ The transverse force components, F_i' and $F_{h.a.}'$ augment the forces of the distributed torso load. A study of the variation in shear stresses and bending moments along the beam simulating the vertebral column provides a clue to the mechanism of back injuries from rear-end collisions. No attempt will be made to quantify shear stresses and bending moments, except to indicate relative orders of their magnitudes distributed along the vertebral column during collision acceleration.

The shear diagram (third from top of Fig. 15) is a curve for the beam shown above it in which the abscissa represents distances along the beam and the ordinates represent corresponding vertical shear stresses.

The vertical shear at the left end of Fig. 15 increases from the abscissa an amount representing the shear stresses applied to the junction of the base of the spine with the hip girdle by F_i'. The vertical shear progressively increases for vertebral sections to the right because of augmentation by the lower trunk mass, to the onset of back support forces, $F_{b.s.}$. As the back support forces increases to maximum, for analysis of sections further and further to the right, shear stresses decrease to zero and then increase in the opposite direction as the back support forces diminish to zero. When $F_{b.s.}=0$, the inflection point in the shear curve is reached for the second time and thereafter the contribution to vertical shear by the distributed load of the torso diminishes until the distributed load becomes zero. This point represents the beginning of the neck, assumed to be of negligible weight. Shear stresses remain constant, therefore, for sections further to the right, terminating at the center of mass of the head.

The moment diagram (lowest curve, Fig. 15) is a curve with distances along the abscissa corresponding to positions along the beam

above it and ordinates representing bending moments for corresponding sections of the beam. Considering sections once again from left to right, the bending moment at the left end is zero because F_i' operates through a moment arm of zero length. Moments for sections progressively to the right increase as a result of contributions of the distributed load and bending moment distances, augmented by the concentrated load, F_i' to the onset of back support forces. As the section approaches the center of pressure of the back support forces, the bending moment is maximum and decreases thereafter by the off-setting effect of the distributed load and $F_{\text{h.a.}}'$ to the right of $F_{\text{b.s.}}$. The bending moment decreases linearly from beyond shoulders to zero at $F_{\text{h.a.}}'$, for reasons (zero mass of neck) described in connection with the shear diagram.

The vertical alignment of certain sections of the curves, considered with the diagrams of Fig. 15 suggest the following:

(a) Substantial shear forces prevail at the junction of the spine with hip girdle during a rear-end collision, but appear not to be sufficient to cause injury. Bending moments are zero or negligible.
(b) At the center of pressure of the seat back, bending moments have increased to a maximum but shear stresses are zero, or nearly zero.
(c) On either side of the seat back center of pressure zone, there exists combinations of maximum shear stresses and near-maximum bending moments that may readily reach injury producing magnitudes.
(d) A substantial residual shear stress prevails at the base of the skull.

The above statements may help explain the presence of mid-back and low-back injuries from rear-end collisions even though that section of the back is supported by the seat-back rest, at least prior to impact.

Individual differences, the non-uniformity of strength of the vertebral column, the non-uniformity of weight distribution of the torso are examples of variables that operate to alter conditions from the above simplified evaluation.

The Automobile has long been a symbol of American achievement and independence. For some, it is their most valued possession. Others regard it as an efficient intra-city form of transportation, and no more. Regardless of its relative individual importance, nearly all Americans own or ride in automobiles and more Americans are accidentally killed by automobiles than by any other means.

Admittedly, many of these accidents are unavoidable but we now know that the majority of the ensuing motorist injuries are avoidable. A few of these injury producing causes and solutions have been discussed. Many others may be found in the technical papers of research organizations within universities, the United States Armed Forces and the automotive industry. Fortunately, the problem has been identified, many solutions recommended and some safety devices are already incorporated in late model cars. Public acceptance of safety devices and design innovations known to reduce motorist injuries represent a hurdle not yet successfully negotiated. Car designers are not exceedingly proud of their Christmas-tree-adorned vehicles—but they sell—which means chrome and design eccentricities have gained public acceptance. No questions are asked concerning the surcharge for over-chromed vehicles. We now are desperately searching for a means to gain public acceptance for motorist safety devices. It is ironic, but we have to sell the American public on the idea of protecting their own lives. Automobile manufacturers stand ready to equip cars with a number of valuable safety modifications, and many design innovations already have been tried on full-scale experimental models. Unfortunately, these improvements add to the cost of the car and, therefore, must await public acceptance before they appear in quantity on

production models. The key to public acceptance of safety devices lies in public information—like I.T.T.E.'s documentary films on experimental collisions.[4] Motorist safety is a problem common to all. How would you motivate the public to purchase a safer car if this were your problem?

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The Psychophysical Testing of an Aircraft Visual Approach Aid[1]

R. H. DAY[2], J. R. BAXTER[3] and J. C. LANE[4]

An aircraft visual approach aid, based on the perception of a misalignment between bars of lights on the ground, is described. Psychophysical tests to establish its sensitivity at long range under various viewing conditions are discussed, including tests in the field and in a laboratory simulator.

INTRODUCTION

Over the last decade a high proportion of all aircraft accidents has occurred during the approach and landing phase, and the majority of these have resulted from misjudgments by the pilot rather than mechanical failure. There is a good working hypothesis concerning the kind of information required for making judgments about position and direction of motion during the landing approach, and this is solidly based as regards alignment in the horizontal plane. But it is much less clear which visual cues are actually used by pilots in making vertical plane judgments. A questionnaire recently answered by 172 civil and military pilots,[1] including instructors, has revealed a considerable amount of uncertainty and difference of opinion. The evidence suggests, however, that favoured visual cues are apparent changes in runway length and shape and apparent movements of objects on the ground.

It has been pointed out by the International Civil Aviation Organization[2] that only a small proportion of approach accidents occur when visibility through the atmosphere is marginal. A large proportion occur in moderate to good visibility when the visual cues provided by objects on the ground are reduced. This can happen, for example, at night over unlit areas or in daylight over sea or featureless terrain, particularly when the horizon is obscured.

The visual information available to the pilot in making his judgments varies widely from one airfield to another and is readily degraded by changes in natural lighting and atmospheric conditions. Attempts have been made to provide assistance by illuminating critical objects and areas near the runway threshold and painting patterns on the runway. These measures do not provide the pilot with direct glidepath information; they merely augment the scarcity of natural cues and leave him to make his usual judgments. A more logical solution seems to be to provide a direct indication of deviations from a predetermined glidepath by means of a device in the aircraft or on the ground.

U.S.A.F. statistics quoted in a recent British report[3] indicate a sevenfold increase in undershoot accident rate with the transition from piston engines to jets. With the increasing use of jet aircraft in both civil and military operations, the need for some form of approach aid is now receiving wide recognition.

The purpose of this paper is to describe a ground based approach aid, known as the Precision Visual Glidepath, and to outline a number of psychophysical tests which have been applied to it. The results of some of these tests should be of general interest because they apply to other problems concerned with visual acuity at long range.

PRECISION VISUAL GLIDEPATH

The Precision Visual Glidepath (P.V.G.) is a system which defines a predetermined glidepath by the alignment of two bars of lights, one white and one amber, as shown in Fig. 1. Fig. 2 illustrates how any departure from the

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1 This article is based upon material contained in Human Engineering Note 5, published by Aeronautical Research Laboratories, Department of Supply, Australia.

2 Department of Psychology, University of Sydney.

3 Aeronautical Research Laboratories, Department of Supply, Australia.

4 Department of Civil Aviation, Australia.

glidepath is indicated by movement of the white bar in relation to the amber. If the aircraft descends too low a red flashing warning light comes into view. The slope of the glidepath and the tolerance allowed before the appearance of the warning light are determined by the geometry of the system.

Details of the principles and design of the P.V.G. have been described elsewhere.[4] The 25-ft elevation of the amber lights has been made acceptable by the use of frangible poles. These have been shown to shatter without damage to an aircraft wing if one should strike them. The W.A.D.C. "Double Bar Ground Aid" and the U.S. Navy's "Pomola" are similar in principle but on a smaller scale and consequently they have a shorter useful range.

Since it was hoped to use the P.V.G. up to an altitude of about 2000 ft on a 1 in 20 glidepath (2.86°) it was necessary to test the effectiveness of the signal at ranges up to about 7 nautical miles.

A full-scale representation of the P.V.G. light display was set up on an airfield near Melbourne so that it could be viewed from an observation point on a range of hills at a distance of 6.8 nautical miles. This representation consisted of 16 poles with some 72 lights which, by appropriate switching, could be made to present 21 different misalignments within the range ± 14 ft (± 70 sec of arc at the observer's eye).

Because of difficulties in conducting field experiments involving long distances, it was considered worth while to construct and validate a $\frac{1}{1000}$ scale laboratory simulator of the display. This consisted of an internally illuminated box with a series of 0.006 in. holes drilled in its face. These holes formed P.V.G. patterns with various misalignments and a metal slide with an appropriate aperture was arranged to expose one pattern at a time.

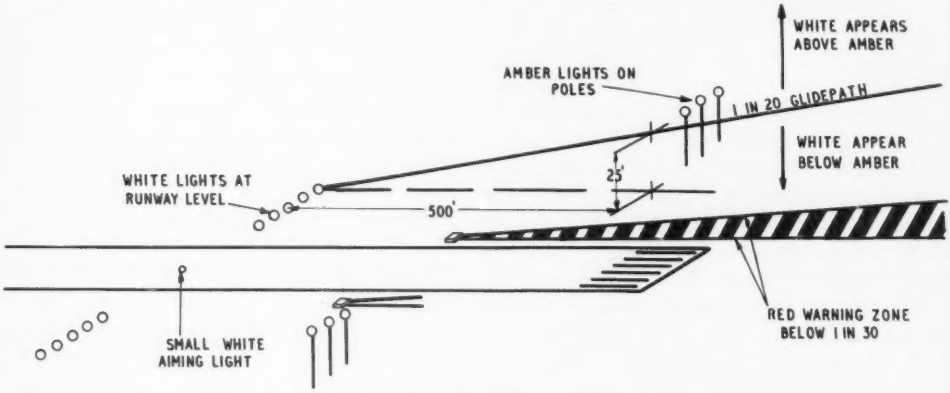

Fig. 1. Perspective diagram of P.V.G.

PSYCHOPHYSICAL TESTS

Four psychophysical experiments concerned with the judgment of P.V.G. misalignments have been carried out:

1. Determination of misalignment thresholds for detection and operational decision.
2. Validation of laboratory simulator.
3. Effect of an adjacent runway light pattern.
4. Effects of an aircraft windscreen and atmospheric attenuation of the display.

A group of 10 pilots who had had operational experience on P.V.G. and 35 non-pilots participated as observers in the first two experiments. The observers for the third and fourth experiments were drawn from among the non-pilot group, all of whom had been given the

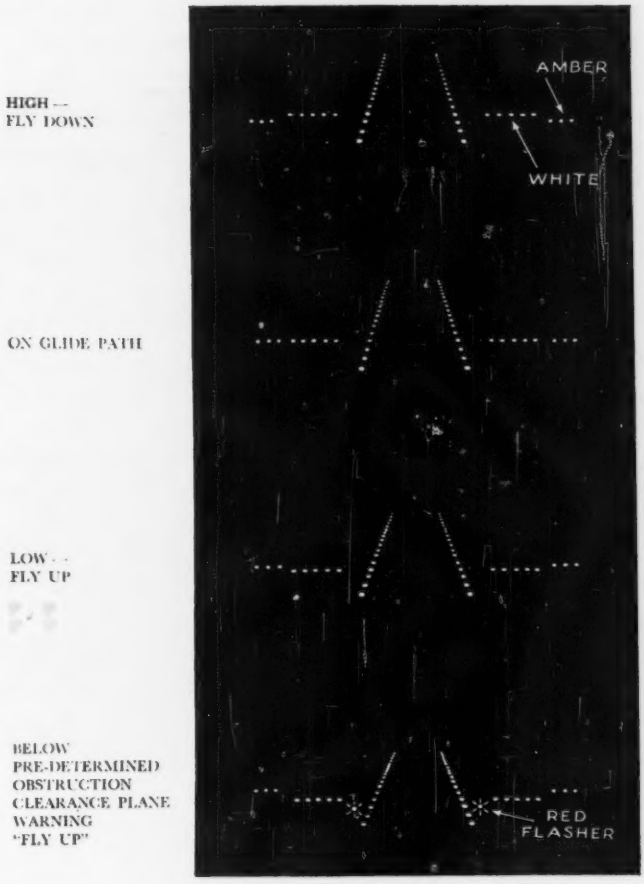

Fig. 2. P.V.G. as seen by the pilot.

aircrew test for visual acuity and shown to have at least 20/30 vision in each eye.

Determination of Misalignment Thresholds for Detection and Operational Decision

In the initial field test 10 pilots were required to indicate whether the misalignments were sufficient to justify flight path corrections up or down or whether they would remain on the same flight path. The 35 non-pilots, on the other hand, were asked to judge whether the white bar was low, high or in line with the amber; in other words they were required to make a threshold judgment.

Before the test both groups of observers were briefed on the nature of the display and the type of judgment they would be required to make. After an initial demonstration 16 different misalignments, in the range ± 70 sec of arc, were each presented three times in random order. Each exposure was preceded by a blue warning signal and lasted for 3 sec.

During the course of the field test the view of the display from the observation point on the hill was slightly obscured by mist, which

TABLE I

Results from Field and Laboratory Tests

	Point of Subjective equality	*Difference limen*	*95 per cent Misalignment (white low or fly up)*	*95 per cent Fiducia limits of 95 per cent misalignment*
			(sec of arc, white above amber)	
Field test				
Pilots	−4.2	25	−54	−61, −48
Non-pilots	−2.6	12	−39	−42, −36
Laboratory test				
Pilots: Set 1	−1.1	23	−54	−61, −48
Set 2	−3.1	19	−55	−62, −49
Non-pilots: Set 1	−2.7	13	−39	−42, −36
Set 2	−2.8	7½*	−22	−24, −19

* Mean 75 per cent point for two-choice test.

thickened as the test progressed. Shortly after the 48 exposures, the display was completely obscured and further tests would not have been possible.

The psychophysical results, including the points of subjective equality (P.S.E.), the difference limens (D.L.) and the 95 per cent misalignments with their fiducial limits are shown in Table I. The misalignment not exceeded on 95 per cent of occasions has been taken as a convenient limiting value.

The results show that there is a consistent difference between the misalignment considered by pilots to be worthy of correction and the misalignment threshold established for non-pilots. This difference is apparent both in the D.L. and the 95 per cent misalignment.

In arriving at the tabulated results, probit analysis has been used. The experimental points established in the field tests are shown, with their fitted probit lines, in Figs. 3 and 4. It can be shown that consistency of judgment,

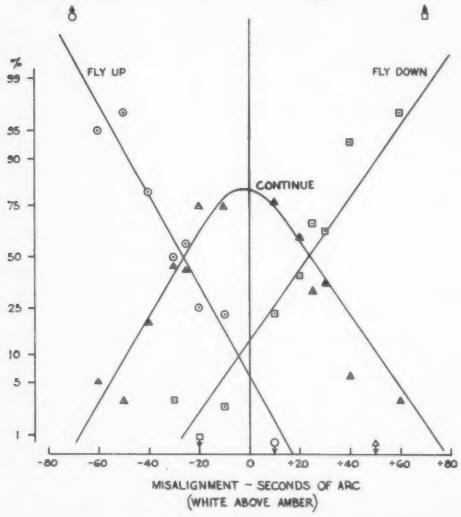

Fig. 3. Results for pilot group in the field test.

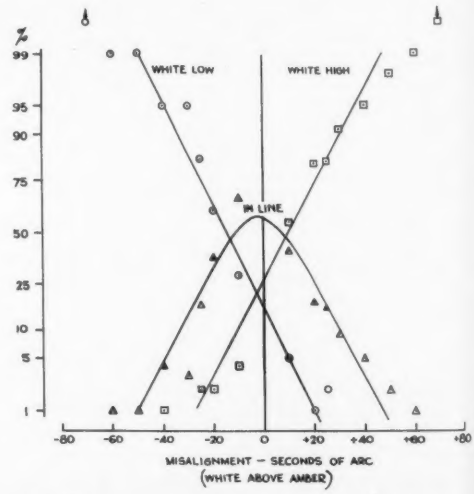

Fig. 4. Results for non-pilot group in the field test.

as represented by the slopes of the probit lines, does not differ significantly between pilots and non-pilots.

Validation of Laboratory Simulator

Prior to the simulator tests, the simulator was taken to the hill observation site on a clear night to match its brightness against that of the full-scale display. Since the field tests, using the full-scale display, were conducted on a misty night, the simulator would have been brighter than the full-scale display on that occasion.

The same observers took part in the hill and laboratory tests so that it was necessary to minimize practice effects. About half of each group participated in the field tests first and then in the laboratory, while the other half observed in the reserved order.

The test consisted of two sets of 48 observations, each consisting of 16 misalignments presented three times in random order. The pilots were asked to make the same three-choice judgment in each set, but the non-pilots were required to make a two-choice judgment in the second set ("white high" or "white low"). The briefing and test procedure in the laboratory were essentially similar to those in the field test.

The results of the laboratory test are shown in the lower portion of Table I. The application of a χ^2 test shows that there is no significant difference between the results for non-pilots in the field test and their results in set 1 of the laboratory test. Set 2 of the laboratory test is not comparable because only two choices were involved. The pilot sample was too small to allow a χ^2 test but it seems clear from Table 1 that, again, there is no real difference between the field and laboratory results. The simulator may therefore be regarded as giving a valid representation of the full-scale display for the purpose of other tests.

It is interesting to note that the P.S.E. in both field and laboratory tests occurs when the white bar is 1 to 4 sec of arc below the amber. The sign test shows that this effect is significant but no explanation has been found.

Effects of an Adjacent Runway Light Pattern

During the first two experiments it became clear that some observers were basing their judgments on an apparent slope of the bars rather than on the misalignment between white and amber. For example, when the white bar was below the amber, the pattern would be perceived as a shallow V.

Due to perspective, rows of runway lights appear to be displaced from the vertical when viewed from a shallow angle and, in accordance with Zöllner's illusion, the apparent slope of one line is influenced by the slope of an adjacent

TABLE II

Runway Light and Windscreen Effects

	Point of subjective equality	95 *per cent Misalignment* (*white low or fly up*)	95 *per cent Fiducial limits of* 95 *per cent misalignment*
		(set of arc, white above amber)	
Runway lights			
without runway	−3.6	−36	−40, −33
with runway	+1.0	−33	−37, −30
Windscreen			
A. *Unobstructed*	−2.4	−28	−35, −24
B. *Dry windscreen*	−2.3	−23	−29, −19
C. *Wet, normal intensity*	−3.3	−31	−37, −26
D. *Wet*, 75 *per cent intensity*	−1.9	−34	−41, −29
E. *Wet*, 50 *per cent intensity*	−0.6	−42	−50, −36

line. It therefore seemed advisable to establish whether the inclusion of rows of runway lights in the centre of the display would affect judgments of misalignment.

The runway light pattern, as perceived from a range of 7 nautical miles, was simulated by drilling holes in the blackened surface of a piece of edge lit perspex[1]. This was mounted on the slide of the simulator so that it would always appear in the correct relationship to the exposed P.V.G. pattern.

Following a slightly modified briefing, 19 of the non-pilots were tested with and without the runway light pattern. In each condition 13 different misalignments were presented three times in random order.

The application of the χ^2 test to the results, which are summarized in Table II, shows no significant difference between the two conditions. However it will be noticed that the

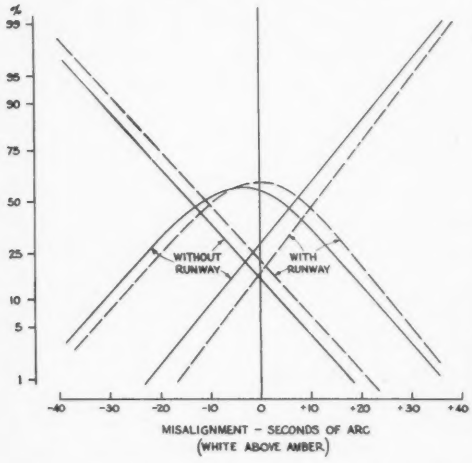

Fig. 5. Comparison of judgments with and without runway.

inclusion of the runway light pattern is accompanied by a reversal in sign of the misalignment at the P.S.E. The probit lines for the two conditions are compared in Fig. 5.

1 Ed. note: similar to Plexiglass.

Effects of an Aircraft Windscreen and Atmospheric Attenuation of the Display

It was thought that presence of a windscreen between the observer and the display as well as deterioration in atmospheric conditions

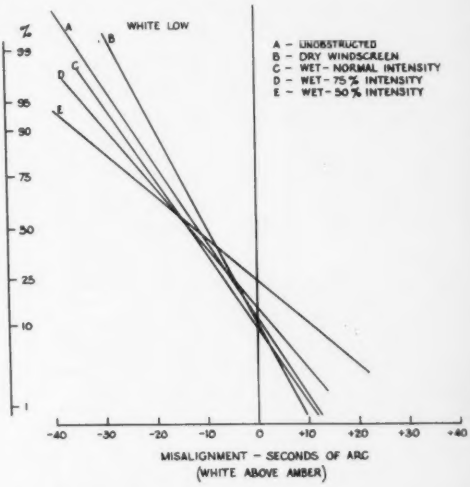

Fig. 6. Comparison of "white low" judgments for five viewing conditions.

would adversely affect judgments of misalignment. To test these effects a small cabin with an aircraft windscreen and wiper was constructed, and provision was made to blow water on to the windscreen. The rate of water deposit was adjusted to correspond to flight through moderate rain (0.75 in/hr) at 110 knots. To simulate the effects of various atmospheric conditions, including the presence of rain, between the aircraft and runway, a means of reducing display intensity was provided.

Twelve of the non-pilots were tested under five conditions of viewing:

A. Unobstructed view of display.
B. View through a dry windscreen.
C. View through a wet windscreen with the display at normal intensity.

Information for Contributors

This journal publishes original articles which increase and diffuse the knowledge of man in relation to machine and environmental factors in all their ramifications, pure and applied. Evaluative reviews of the literature, definitive articles on methodology and procedure, technical articles of original research that are broad in scope, articles of general professional interest, and articles which stress utilization of information will be considered for publication.

Such articles should include subject matter not systematically covered by other journals. They should be interdisciplinary in nature, appealing to a group of readers with diverse professional backgrounds such as anthropology, engineering, medicine, physiology and psychology. The presentation should encourage the development of a language and concepts common to the many fields of interest touching upon human factors. Brevity in titles and compactness of presentation is desired. A general history of the subject should not be given unless it is a major concern of the paper, is not commonly known and is properly documented. A history is appropriate in a review paper.

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4. Papers will be published as quickly as possible after acceptance. Short communications such as Letters to the Editors, Questions and Answers, and Notes will receive priority for publication.
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7. Papers must be written in English.
8. The essential contents of each paper should be stated in an abstract.
9. Illustrations should be separate from the typescript of the paper and legends should be typed on a separate sheet from the illustrations. Line drawings which require redrawing should include all relevant details and clear instructions for the draftsman. Illustrations for reproduction should normally be about twice the final size required, with letters approximately $\frac{1}{32}$ in. to $\frac{3}{16}$ in. high. Photographs should be used only where they are essential. Figures should be numbered consecutively in Arabic numerals.
10. In the typescript indicate by a brief note where a table or figure is to appear, thus:

(Insert Figure—about here)

11. Tables should be made proportional to the journal page. They should avoid repeating material shown in figures. All tables should have titles, and be intelligible without reference to the text. Every table and column should be provided with an explanatory heading. Units of measure must be clearly indicated.
12. References should be noted by Arabic numeral superscripts in the text. References will be arranged alphabetically at the end of the article, with the author's surname first, followed by his initials, the title of the journal or the book, the volume number, first page number and year. The publishing house, city of publication and date of publication should be noted for books.
13. Authors will be charged the full cost of alterations and corrections due to errors which they make on proofs.
14. Footnotes are discouraged. If used, number from 1 upwards in Arabic subscripts. Type footnotes on a separate sheet, apart from the manuscript proper.
15. Supplementary material to articles in the Journal may be deposited with the American Documentation Institute. Authors preparing such material should prepare drawings which are jet black on white, and textual material should be single spaced on standard size paper. The author's name, permanent address and institution should be noted. The supplementary material should be sent with the article to the Editor-in-Chief, not to the American Documentation Institute.

Readers interested in ordering supplementary material may write to the ADI Auxiliary Publication Project, Photoduplication Service, Library of Congress, Washington 25, D.C.

D. View through a wet windscreen with the display at 75 per cent intensity.
E. View through a wet windscreen with the display at 50 per cent intensity.

In each of these conditions eleven different misalignments, within the range ±50 sec of arc, were presented twice in random order.

The "white high" probit lines for the five conditions are compared in Fig. 6. These and the summary of results shown in the lower portion of Table II, suggest that the 95 per cent misalignment tends to increase as the viewing conditions are degraded. The application of the "t" test to a line of best fit through points representing the 95 per cent misalignments, assuming equal intervals between the five conditions, shows that the slope of the line is just significant.

The twelve observers were asked to express their views on the adequacy of the signal in conditions 3, 4 and 5. Although the experimenters had thought that, in the most degraded condition, the signal would be generally classed as inadequate, only two of the twelve considered it "unusable" and two others considered it "of doubtful value".

CONCLUSIONS

Field tests, using 10 pilot observers with P.V.G. experience, showed that, at a range of about 7 nautical miles in misty and deteriorating weather conditions, 95 per cent of pilot judgments would be in favour of "fly-up" corrective action during a P.V.G. approach when the misalignment was 54 sec of arc. Tests with 35 non-pilot observers showed that, under the same conditions, a misalignment of 39 sec would be detected in 95 per cent of judgments.

The analysis of a similar series of tests, conducted in the laboratory using a $\frac{1}{1000}$ scale simulator matched in intensity with the full-scale display in clear conditions, indicated that the simulator was a reasonably valid representation of the full-scale display.

In the field and laboratory tests both pilots and non-pilots consistently judged the white and amber bars to be in line when, in fact, the white bar was from 1 to 4 sec of arc below the amber. No explanation of this effect has been found.

A test conducted in the laboratory using 19 of the original non-pilot observers, failed to reveal any significant effect on misalignment judgments when a runway light pattern was included. However, in the presence of the runway light pattern, the apparent alignment of the bars occurred when the white was slightly above the amber.

A test designed to investigate windscreen and atmopsheric effects, using 12 of the original non-pilot observers, showed a significant trend towards a deterioration in sensitivity of judgment as the signal was degraded. The maximum deterioration was produced by a wet windscreen with a windscreen wiper and a 50 per cent reduction from the normal intensity.

The 50 per cent reduction in intensity was chosen because the experimenters formed the opinion that observers would place little reliance on a display so dim. However, during the tests only 2 out of 12 of the non-pilot observers expressed the opinion that this display was "unusable".

At the maximum range at which an aid such as the P.V.G. might be expected to be used (about 7 nautical miles) the 95 per cent misalignment for pilot correction established in misty weather conditions (54 sec) represents a displacement of 940 ft below the glidepath. This would place the aircraft within the zone of the red flashing warning light, commencing 720 ft below the glidepath at that point. The pilot would therefore be expected to react to the red warning on more than 5 per cent of occasions in such conditions. However, even if he waited for the 95 per cent misalignment, the aircraft would still be above the customary obstruction gradient of 1 in 40 which is 1090 ft below the glidepath at that range.

At closer ranges the sensitivity of the P.V.G. rapidly improves and the 54 sec misalignment coincides with the boundary of the red warning zone at about 5½ nautical miles.

It is clear that sensitivity to misalignment

would decline as the signal was degraded by rain or other atmospheric effects. However the red warning is of higher intensity than the main display and should remain visible up to the point where the main display is completely obscured, thus precluding any dangerous deviation below glidepath.

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Estimation of the Center of Simulated Planetary Bodies[1]

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The task of centering the simulated image of a planetary body on a display representing the viewscreen of a satellite was investigated in a study employing both male and female subjects. It was found that task performance, as measured by relative radial error, is significantly poorer for crescent and gibbous bodies than for full-phase bodies, and that a circular screen is significantly better than a rectangular one. No significant difference appears for the three diameters of planetary image which were tested. There occur large differences among individuals within the subject group, and the male group exhibits lower error scores than the female. The best subject performed at a level of approximately 1 per cent estimation for all conditions. This amount of operator error is theoretically compatible with the requirements for attitude control during the re-entry of a satellite vehicle.

INTRODUCTION

One potentially important task for a satellite passenger is participation in a system for attitude sensing and control. If a manned system is to operate competitively with proposed automatic modes,[3] it is necessary that the functions allocated the operator make best use of his human capabilities. Among the methods of sensing and control which appear particularly suited to the human operator are those which involve utilization of the observed centers of nearby planetary bodies as an attitude cue.

Space vehicle attitude can be referenced to a number of co-ordinate sets; in the case of a satellite, an Earth reference is often most useful. The Earth, when viewed from a circling satellite, presents a disk whose apparent diameter is dependent upon the vehicle altitude. The edges of the disk represent the "horizon" to a satellite-based observer. Local vertical can be related to the line between the vehicle structure and the center of this disk. The sensing and control operation may be described as one of "centering" the disk on an arbitrary display. Similarly, the observed disk of the Moon can be utilized in other methods of computing altitude. Automated methods for utilizing this information are complicated by the fact that the disks do not always appear as full circles. At various times in the satellite's orbit, both the Earth and the Moon can appear in full, gibbous and in crescent phase; thus the center of illumination does not necessarily coincide with the true center of the body.

It may be postulated that the task of centering such a degraded circle on a display could be accomplished by a human operator. But although there have appeared studies in which the satellite pilot is assumed to operate with more conventional attitude displays,[2] we have been unable to locate data pertinent to the suggested "disk centering" mode. The present investigation, then, was designed to provide a preliminary estimate of the operator's ability to determine the center of an observed planetary body.

METHOD

Approach

Because an initial estimate of performance was desired for practical reasons, it was necessary to limit the present study to examination of a highly idealized and simplified situation. Accordingly, we used simulations of planetary bodies which consisted of a uniformly high contrast white stimulus-disk against a black background; and the experimental display-control apparatus represented the utmost in simplicity. Finally, display aids to

[1] The research described in this article was conducted at Systems Corporation of America under Contract AT 33(616)–667 with the Flight Control Laboratory of WADD.

centering were minimized, while unlimited time was allowed for task completion so that the experiment assumedly dealt with maximum levels of performance in the simulated operation.

Apparatus

It was desired to simulate the display situation which might result from a periscope-type lens coupled to a viewing screen in the satellite. The simulation apparatus utilized is illustrated in Fig. 1. Planetary body representations were prepared on 12 in. × 12 in. squares of heavy cardboard; these squares were fastened to the stimulus card tray which slid freely under a sheet of Plexiglass. The Plexiglass was masked with light gray paper, leaving an open area in accordance with the experimental design. By manipulating the handles extending from the card tray, the subject centered the stimulus disk under edge-lit cross hairs in the viewing area. The tray was relatively frictionless and could be brought repeatedly to any specified point. At no time during the positioning portion of a run was the tray itself visible. A fluorescent light was placed at the 12:00 position with respect to the subject and produced a glareless illumination of the display; otherwise, the ambient light in the experimental room was low.

Gathering of positioning error information presented a problem for it was necessary that the true center of the simulated bodies be unambiguously indicated, yet it was required that this indication provide no aid to the subject. The problem was solved by including a seemingly random pattern of "star" dots on the display card. Four of these stars defined lines whose intersection fell at the true center of the body. These lines corresponded to the orthogonal axes of the gibbous and crescent disk but were randomly oriented for the circle. The camera pictured in Fig. 1 swung clear of the viewing area during a trial and was moved in to record the disk-dot situation at the trial termination.

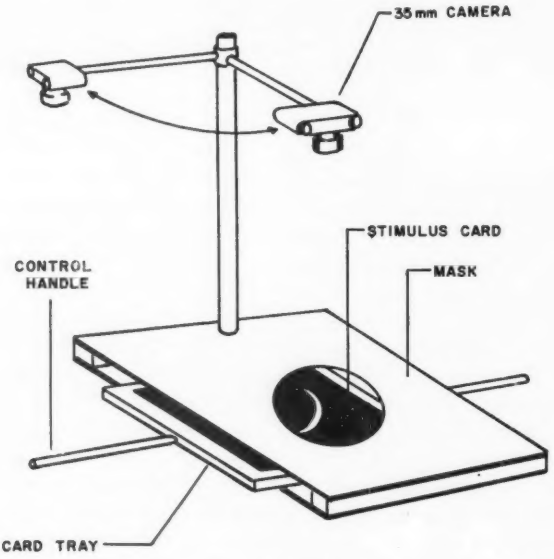

Fig. 1. Sketch of the experimental apparatus; a stimulus card appears on the tray and the circular mask is in place.

Subjects

Six subjects were used, three male and three female. All had normal or corrected vision, and none had had any experience on a similar task. The three male subjects were engineers. The female group consisted of two secretaries and a mathematician. Whereas the female group, except for the mathematician, was relatively unfamiliar with stimulus figures of the type presented, all members of the male group had previously encountered such geometric shapes. Subjects in the male group are referred to as M_1, M_2 and M_3, and in the female group as F_1, F_2 and F_3 in the following sections.

Experimental Design

Three variables were examined in the present study: planetary phase, body diameter and mask (or viewing area) configuration. The three circle diameters used were 2 in., 4 in and 6 in.; a full, a gibbous, and a crescent disk were prepared for each level of diameter. Thus 9 stimulus-cards were available. The gibbous and crescent disks were placed on the cards so that the major orthogonal axes did not coincide with the cross-hairs of the view screen when the tray was oriented as shown in Fig. 1. Both the gibbous and the crescent simulations were prepared by superimposing 45° elipses of appropriate major axis on to circles of the specified diameter. Two mask configurations were employed: an 8 in. diameter circle and an 8 in. by 9 in. rectangle oriented with its long side horizontal. Only the cross-hairs appeared within the viewing area of both masks, and the intersection of the cross-hairs fell at the true center of the view port. Examples of the disk shapes and mask configurations are presented in Fig. 2.

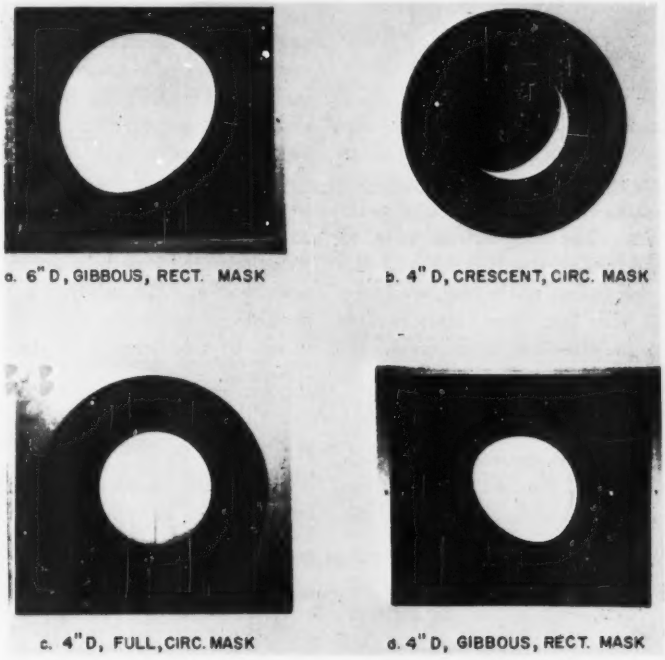

Fig. 2. Sample planetary displays reproduced from 35 mm film record.

A full $3 \times 3 \times 2$ factorial design with one replication was administered to each subject. The resulting 36 treatments were presented in 4 blocks; each block involved a particular mask condition. In every block the 9 stimulus cards were presented in random order and random orientation. Two blocks constituted a replication, and mask order was randomized for each replication.

PROCEDURE

The subjects were shown the apparatus and familiarized with the task. They were told that the stimuli to be shown represented idealizations of spheres in various phases; the gibbous and crescent disks could be thought of as incomplete circles. The instructions were to adjust the disk, using the handles and not changing the orientation of the tray, until they were satisfied that the true body center coincided with the cross-hair intersection.

Each stimulus card was affixed to the tray by the experimenter, the subject being required to bring the simulation disk into view. When the subject reported the disk centered, the camera was positioned and the display situation recorded. A new card was then selected and the procedure repeated. Two-minute rests were given between blocks and five-minute rests between replications.

The film negative for each trial was projected on to a sheet of white paper to three times the original size of the display. The "code stars" were then recorded on the paper as was the point of cross-hair intersection; calibration marks appeared on each negative and were also recorded. The distance R between the true center of the stimulus-disk and the hair-line center was easily measured once the "code star" marks had been connected. Since the cross-hairs appeared on the film and the identifying dots had been placed on the orthogonal axes of the display, it was possible to orient R with respect to either display or stimulus co-ordinates. The only numerical value recorded was the absolute length of the error vector. The calibration marks made it possible to accurately relate the measured R values to true lengths in the actual display apparatus.

RESULTS

The scatter pattern, produced by superimposing all absolute radial errors for all

TABLE I

Analysis of Variance by Ranks

	Phase						*Mask*				*Diameter*					
Subject	*Full*		*Gibbous*		*Crescent*		*Circular*		*Rectangular*		*6 in.*		*4 in.*		*2 in.*	
	R* (*per cent*)	*N*	R* (*per cent*)	*N*	R* (*per cent*)	*N*	R* (*per cent*)	*N*	R* (*per cent*)	*N*	R* (*per cent*)	*N*	R* (*per cent*)	*N*	R* (*per cent*)	*N*
F_1	1.3	3	6.1	1	3.8	2	3.7	2	3.9	1	2.3	3	4.4	2	4.7	2
M_1	0.9	3	0.93	2	1.1	1	0.9	2	1.0	1	0.7	2	0.65	3	1.6	1
F_2	1.0	3	1.9	2	3.1	1	1.6	2	2.4	1	1.8	3	2.2	1	2.1	2
M_2	1.4	3	2.1	1	2.0	2	1.8	2	1.9	1	1.6	3	2.0	1	1.9	2
M_3	1.4	3	1.8	2	2.2	1	1.7	2	1.9	1	1.6	2	1.5	3	2.2	1
F_3	1.2	3	3.6	2	5.5	1	3.0	2	3.9	1	3.7	2	2.1	3	4.5	1
ΣN	18		10		8		12		6		15		13		8	
χ_r^2			9.33				6.00						4.33			
Probability			<0.01				<0.02						—			

Note: N = Rank of score.

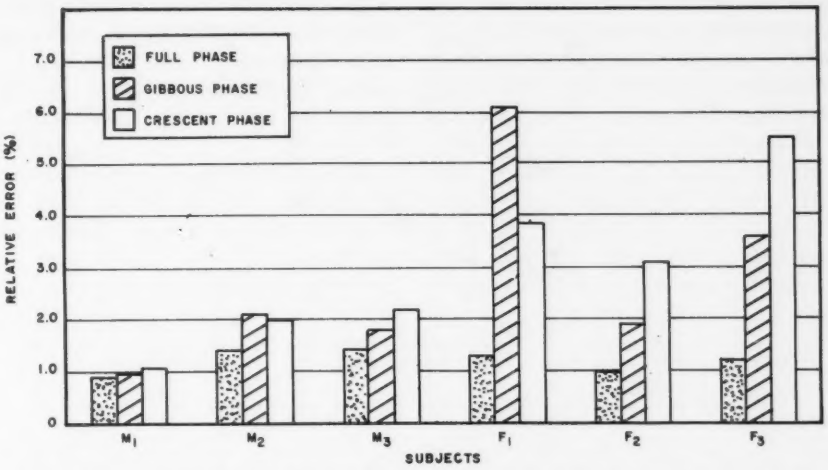

Fig. 3. Relative error of positioning as influenced by the phase of the simulated planetary body.

subjects and referenced to the display cross-hairs, showed the following: a massing of dots near the center, no apparent estimation bias and an approximately equal representation of dots for all quadrants.

These absolute data were normalized by dividing the calibrated R value by the appropriate circle diameter—thus producing a measure of relative error, $R^* = R/\text{diam}$. Now, even if the error scatter were two-dimensional normal, the radial measure would be Rayleigh distributed; in addition, an assumption of variance homogeneity among subjects was not justified. Accordingly, a non-parametric analysis of variance by ranks[4] was utilized to test the significance of the experimental results. The results of this analysis appear in Table I, where values of R^* are presented in terms of per cent error.

The differences in relative error did not prove significant for the three disk sizes, but the subjects performed significantly better with the circular mask than with the rectangular one. In addition, there appeared a significant difference in center estimation for the full, gibbous and crescent phases. Figs. 3 and 4

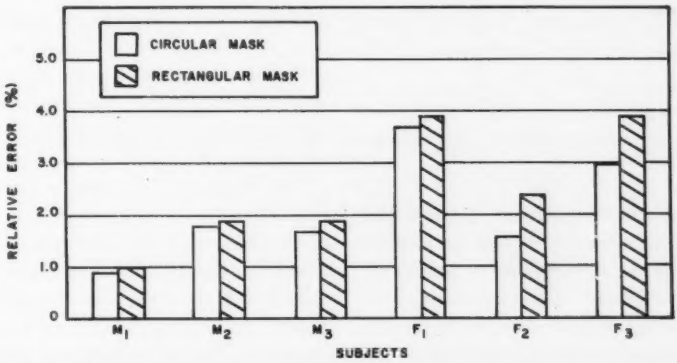

Fig. 4. Relative error of positioning as influenced by the shape of the mask aperture.

illustrate the subject performances on the phase and mask conditions, respectively.

The subjects performed quite uniformly on the full phase condition. The gibbous and crescent figures, however, seriously disrupted the performance of two subjects in the female group. In both cases the relative errors for those conditions far outstrip the errors for the full phase, yet there is no uniformity of preference. This lack of uniformity is also present in the male group but with no corresponding magnitude of error increase. All subjects performed worse with the rectangular mask; four only slightly so, but F_2 and F_3 markedly so.

It is possible to determine the class of positioning errors made if the vector R is referred to the co-ordinate axes of the stimulus figure. Scatter plots for the crescent and gibbous disks appear in Fig. 5; the figures are reproduced tracings from the projected film charts, and the scale dimensions refer to distances on the original figures. Each dot on these plots represents a subject's estimate as to

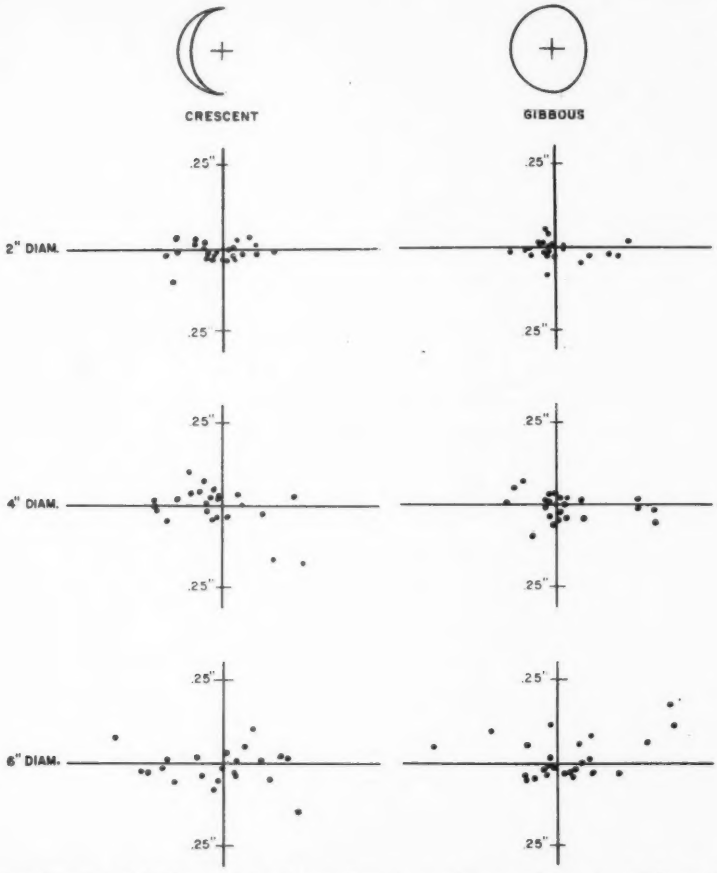

Fig. 5. Scatter diagrams of absolute error, referenced to the co-ordinates of the stimulus figure, for the three disk diameters.

the location of the center of the figure, as inferred from his positioning of the figure on the corresponding trial. The small crescents and gibbous disks are included to aid the reader in orienting the axes on the original display figures.

Note the predictable spread of the scatter for the larger diameter figures. The point of greatest interest, however, is that the error appears essentially bound to a single coordinate axis—the axis of symmetry. There is no obvious bias of estimation along this axis although a dot-count reveals some tendency for the estimates to lie toward the left, or the apparent center of gravity of the pictured body. Very large individual errors occurred for both the crescent and the gibbous conditions. The full-phase disks produced no marked eccentricity of errors and thus are not shown.

Both Figs. 4 and 5 reveal a large variation in performance among subjects, but especially between members of the male and female groups. Perhaps contrary to intuition, subject F_2 was not the mathematician member of the female group; the mathematician was F_1 who performed the poorest. There was an increase of approximately 300 per cent in mean relative error score between the best and the worst member of the subject group. In order to demonstrate the corresponding differences in error variance at the extremes of performance, error plots for the two best (M_1 and M_3) and the two worst (F_1 and F_3) subjects are presented in Fig. 6. These plots include all conditions tested. The error scatter attributable to the two poorest subjects is far greater than that produced by the two best; the latter set of points forms almost a solid mass at the origin.

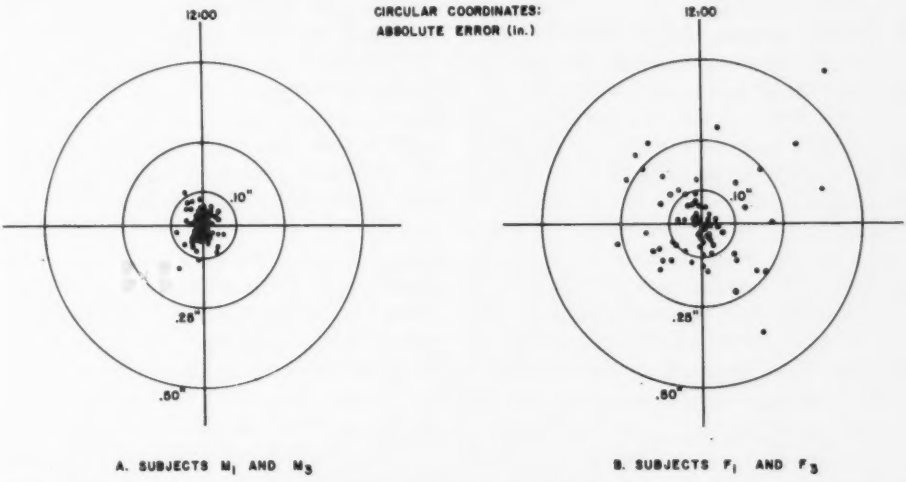

Fig. 6. Individual differences in performance. Scatter diagrams of absolute error, referenced to mask coordinates, for the two best (M_1 and M_2) and the two worst (F_1 and F_3) subjects.

DISCUSSION

The results of the disk centering study indicate the following:

1. Relative errors in center estimation are significantly higher for degraded circles (gibbous and crescent phase) than for full circular disks.
2. The errors of estimation made for the gibbous and crescent disks tend to lie on or near the axis of symmetry.

3. The effect of the circular mask is to significantly better performance over that demonstrated with a rectangular mask.
4. The relative error is not significantly different for the three diameters of disk examined.
5. There are apparently major differences in individual performance and, in this study, a difference between the male and the female groups. The male group exhibited lower mean error scores and a smaller in-group variance.

In addition, it appeared that the distribution of radial error was centered on the origin of the display co-ordinates.

The performance difference under the two mask conditions, while statistically significant by the ranks test, has relatively little practical significance for the three male subjects. The difference might be attributed to the interaction of the circular mask with the large circular disks. It was more difficult to make a gross error with the circular mask because the 1-in. strip of background black between the circular disk edge and the mask provided a useful additional cue. Almost all the subjects reported that they relied heavily on this cue, rather than on the hair-lines, for centering the largest disks. It is obvious that the next stage of display design would include one or more fixed concentric circles in addition to, or perhaps even replacing, the hair-lines. If possible, a variable diameter guide circle (to provide for altitude variations in the satellite) could be incorporated.

The location of the radial error for the gibbous and crescent bodies has much interest, yet in the actual satellite situation it would seemingly be impossible to guarantee any particular initial orientation of the displayed disk. If random orientation is assumed, it is also necessary to assume a random distribution of error about the display co-ordinates. It is therefore not likely that the variance information could be economically utilized for automated correction of the human estimate.

The fact that phase is significant to performance might conceivably have a bearing on the scheduling of attitude operations. Attitude sensing and control would probably be an intermittent task for the satellite pilot. The results of the present study indicate there would be an advantage in selecting orbital positions at times when the observed planetary body is in full phase. But a partial negation of this statement lies in the very slight actual performance difference exhibited by the best subject (M_1) in the three-phase conditions. It appears that performance is essentially independent of phase for a good subject.

The apparent difference in estimation ability among the subject group is perhaps one of the more important results of the study. The implications are twofold. First, it is indicated that personnel selection would be mandatory if it is desired that performance be optimal. Secondly, the performance difference seemingly breaks down to a difference in experience with similar figures. Characteristically, the better subjects (except for F_2) stated that they utilized previously known geometric relations in the figure and display to aid them in the estimation task. If this is so, then it is likely that specific familiarization and practice with variable-phase simulators would tend to lower both the mean error and the variance. In the present study, all the subjects but F_1 improved their scores on replication.

Although it cannot be ascertained that the gibbous and crescent conditions chosen represent "worst" cases, we may state that on the basis of present results an optimum human operator utilizing even a minimal display configuration will function approximately as a "1 per cent component" in estimating the center of simulated planetary bodies. His actual error function can only be expressed as a probability distribution over the display space. On the assumption that the relative error has a two dimensional Gaussian distribution with zero mean and equal x and y variance, we may utilize the acquired data to construct concentric probability circles for the relative radial error

function of M_1, the best performer in the subject group. This is done by computing the mean radial error (m.r.e. $= \Sigma R^*/n$) measure of dispersion and utilizing the corresponding radii of probability circles tabulated in Locke.[1] The resulting computations indicate that the relative error will fall within 0.98 per cent with probability 0.50, within 1.7 per cent with probability 0.90, and within 2.3 per cent with probability 0.99 over the range of disk diameters tested.

From a satellite 1600 kilometers above the surface of the Earth, the horizon disk subtends a visual angle of 106°. If a 150° periscope lens with some edge distortion is postulated, the resulting display approximates that of the mean simulated body (4-in. diameter) on the circular mask. According to the theoretical probability distribution for subject M_1, we would expect a terminal centering accuracy within a conical half angle of 1.7° from the satellite approximately 90 per cent of the time.

According to numerical results derived from the data of Chapman,[5] positioning of a satellite vehicle (having a substantial lift/drag ratio) within the permissible entry corridor to Earth necessitates attitude control on the order of $\pm 1.3°$. This value corresponds in meaning to the half angle mentioned above. It represents an allowable attitude deviation for a maximum satellite deceleration of 5G; because there is a trade-off between entry corridor width and G load, the accuracy needed can be decreased if G tolerance is widened. The presence of a human operator within the vehicle does impose a boundary on the acceleration; but with proper body support and positioning, loads to 10 G should not be serious. The prognosis for human attitude control, then, is evidently marginal but promising; a comprehensive evaluation must include considerations of individual differences, probability distributions of error magnitude, and permissible stress, as well as means for improving performance of the operator.

Extension of the present study might take one of two directions. It would be possible to examine some of the neglected variables by utilizing the previously described display simulation. Such studies might:

1. Provide better simulation of the horizon disk as it is liable to be presented on the satellite display screen. That is, examine the effects of terrain and cloud pattern, blurring of the disk edge, "ringing" in the dark segments of crescent and gibbous phases due to diffusion of light through the atmosphere, and of various filters (infra-red for example) which might be utilized to alter the disk characteristics.
2. Manipulate display-control variables in the simulation. For example, the actual viewing distance might be more rigidly controlled, as could the time allowed the subject for his decision. By shortening this time duration, it might be possible to approach more closely the conditions of dynamic control and also to provide a useful estimate of performance degradation in more critical situations. Finally, the effect of concentric guide-circles might be evaluated.

The second line of attack would essentially discard this highly simplified apparatus and:

3. Provide a more elaborate display-control simulator which would allow for dynamic programming and manipulation of the horizon disk. The most important aspects of the human operator's task will be his action in two situations: (a) stabilization and orientation of a tumbling satellite, and (b) transfer from one stable attitude to another stable attitude. These tasks will involve a dynamic display condition and control response, and the operator function probably will require two-dimensional tracking with an apparently spinning horizon disk.

The program of paragraph 3 seems by far the most important to specification of an actual system, but it would have to include the considerations of the first two paragraphs for completeness. The results of the present study,

in addition to providing preliminary performance data, appear applicable to the final portion of a more complex dynamic response task. Because the indicated levels of performance appear promising, it is felt that further investigation is justified.

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Manual Application of Impulses while Tractionless

ERNEST DZENDOLET, Behavioral Sciences Laboratory, Wright Air Development Division, Wright-Patterson Air Force Base, Ohio.[1]

The percentage of 20 naïve subjects who, while tractionless in a horizontal plane and anchored by one handhold, push in or pull out a plunger in one motion against various frictional forces and travel distances, decreases directly as the force and distance required. With large-force impulses, the impulse is linear and the situation can be described by the impulse = momentum theorem) $\int_0^t F dt = mv_1 - mv_0$. The shape of the impulse is saw-toothed, and its area approximated by taking three-fourths of the area of a rectangle whose base is the duration, and height, the force of the impulse. For this experiment, the maximum duration of an effective impulse for a required force of 40 lb is 0.5 sec for a push-in, and 0.3 sec for a pull-out impulse.

INTRODUCTION

In a previous study on the application of manual forces under tractionless conditions,[1, 2] it was shown that the maximum forces which could be applied for periods of time exceeding 4 sec were small in magnitude and were a function of the angle of the handhold used. The largest mean value obtained under the best conditions of handle orientation was only 4.1 lb, when the point of application of the force was 2 ft away from the handhold.

On the other hand, it was found that where the subject could apply a force of shorter duration, he was able to exceed this value easily. The reaction to this impulse, as would be expected, was enough to move the subject away from the point of application. It was of interest, therefore, to determine what types of impulses could be applied by a subject, as a function of certain external constraints, and as evaluated by some appropriate criterion. If the general forms of these impulses could be determined, then quantitative calculations could be made concerning reactions to the applied impulses, and upper bounds for force requirements could be imposed on equipment to be handled under tractionless conditions, i.e. in space. These quantitative calculations could be made by evaluating the impulse-momentum theorem: $\int_0^t F dt = mv_1 - mv_0$.

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METHOD

Apparatus

The same air-bearing "scooter" (Fig. 1), strain gauge transducer or force-bar, and handhold as used previously were employed. The handhold was placed in the horizontal or most effective position. The force-bar was modified by attaching a new piece of apparatus to it (see Fig. 2). Essentially, it was a cylindrical steel plunger which could travel inside a steel tube. A movable steel stop could be placed in any one of a number of slots in the tube so that the plunger was limited in its travel to distances ranging from 1.4 to 6.5 in. Furthermore, the tube had a split Teflon collar near its opening which could be tightened around the plunger, thus making a greater force necessary to move the plunger.

Subjects

Twenty subjects, all male students from a local university, were used. They ranged in weight from 142 to 230 lb, with a median weight of 172.5 lb. In age, they ranged from 18 to 23 years. All were naïve with respect to the apparatus and the experiment.

Procedure

A subject was instructed to sit on the scooter, with his left hand on the handhold. With the right hand, he was to push the plunger, with one motion, as far as it would

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Fig. 1. A subject on the "scooter" showing the scooter itself, floor plate, handhold, and transducer. The air hose supplying the scooter is at the lower right.

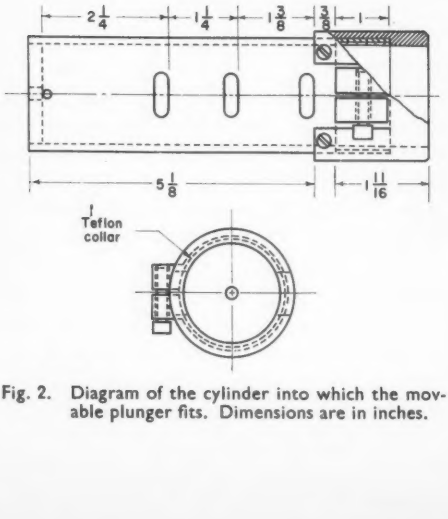

Fig. 2. Diagram of the cylinder into which the movable plunger fits. Dimensions are in inches.

go in the tube. He was further told that the force he applied was to be along the line of the longitudinal axis of the plunger and tube, and that he could use the palm or the heel of the hand to do this. He was cautioned not to hit the plunger a sharp blow, but otherwise to move the plunger as quickly or as slowly as he wanted. The warning about the sharp blow was merely to save training time, since such a blow produced little movement of the plunger.

There were two conditions under which the subject was to perform the task of pushing in the plunger. The first was with air blowing through the air-bearing pads of the scooter, making the subject tractionless. The second was with the subject seated, under normal

frictional conditions. The order of presentation of these conditions was the same for all the subjects.

The various forces against which, and travel distances through which, the subjects were to push the plunger were presented to all the subjects in the same order, that of presumed

TABLE I

Order of Presentation of Tasks to the Subject shown by the Arabic Numerals Within the Cells. Magnitudes of Required Forces and Travel Distances are shown in the Column and Row Headings

	Travel distance in inches			
	1.4	2.8	4.0	6.5
Force in pounds				
5	1	2	3	4
10	5	6	7	8
20	9	10	11	12
40	13	14	15	16

increasing difficulty as given in Table I. The order was chosen so that a task requiring a small force and short travel distance would not follow a task requiring a large force and long travel distance. If a random order had been used, a very large force might be applied to a small force situation. It was hoped that just adequate impulses would be used by the subjects when the tasks were presented in the order of presumed increasing difficulty.

In addition to "push-in" forces, "pull-out" forces were also measured. The subject was instructed to push the plunger in, wait for a signal from the experimenter, and then pull the plunger out. The experimenter then changed the force, or the travel distance on the tube, whichever was necessary, before the next push and pull. As mentioned above, when the subject had performed the task with air activating the scooter and making it frictionless, the air was shut off and the subject went through the entire procedure again, still seated on the scooter, with normal friction to aid him in his task.

Four practice trials were given to each subject before the recording of data. The lowest force and one or two of the intermediate travel distances were set on the apparatus for this purpose.

The specific travel distances and forces used in the experiment were selected arbitrarily so as to cover a reasonable range of values in a non-linear manner. The tightness of the Teflon collar to give the approximate forces chosen, was determined by the experimenter by trial and error before the experiment.

Scoring

Scores consisted of the percentage of subjects who could perform the push, or the pull, in one continuous motion under the various conditions. A subject was considered to have failed in the task if he could not perform it at all, or if more than one impulse were required.

RESULTS

Qualitative Results

Observation of the subjects showed that the technique used to perform the task depended on the force, and on the travel distance required. At the lower values of both distance and force, the subjects placed themselves approximately halfway between the handle and the force-bar, i.e. the point of application of force. The push and the pull were performed with the right arm. The reaction to this applied impulse was apparently countered primarily by the reaction to the left hand acting on the handhold. At the higher required values of force and distance, the subjects placed themselves directly behind the force-bar, and the push and the pull were again performed with the arm, but the force was applied primarily against the inertia of the body. It was impossible for the subjects to counter these force values with the aid of the handhold, and they relegated the handhold to an attachment point about which the body revolved and could be repositioned after the task was performed. The impulse delivered was now a linear one, since the entire body was behind the force-bar.

One interesting, and probably important,

technique used by certain subjects under tractionless conditions was the following one. If, after a long-travel-distance, push-in impulse the subject held on rigidly to the plunger, he tended to pull the plunger out again, especially at the low-force values. However, if the subject absorbed this force by allowing himself to move a reasonable distance backward while still holding on to the plunger, the subject could bring himself to rest without moving the plunger at all. Thus the subject could maintain his position without using a handhold.

Quantitative Results

Table II gives the percent of the 20 subjects who were able to perform the task under tractionless conditions as a function of the force and travel distances required. Table III is a similar table for the control situation with normal friction present. The table is abbreviated since all subjects gave correct responses for forces of 5 and 10 lb.

TABLE II

Percentage of Subjects Performing the Impulse Task Correctly under Varying Conditions of Required Force and Travel Distance under Tractionless Conditions

	Travel distance in inches			
	1.4	2.8	4.0	6.5
Force in pounds				
5 push	100	100	95	75
pull	95	90	85	70
10 push	90	100	100	85
pull	90	95	95	65
20 push	90	90	85	65
pull	85	75	65	70
40 push	90	75	80	30
pull	75	50	50	30

TABLE III

Percentage of Subjects Performing the Impulse Task Correctly under Varying Conditions of Required Force and Travel Distance under Normal Frictional Conditions

	Travel distance in inches			
	1.4	2.8	4.0	6.5
Force in pounds				
20 push	100	100	100	100
pull	95	100	100	100
40 push	95	90	100	95
pull	100	95	100	95

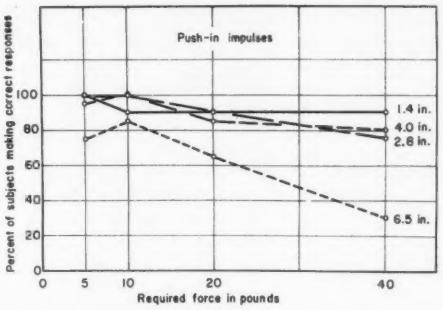

Fig. 3. Plot of the percentage of subjects making correct "push-in" impulses as a function of the required force in pounds.

Fig. 3 shows a plot of the correct responses for a push-in impulse *vs.* the force necessary to move the plunger. Fig. 4 shows the same variables plotted for the pull-out impulses. In Fig. 3 it can be seen that there is a tendency for the percentage of correct responses to drop as a function of increased force required. This is

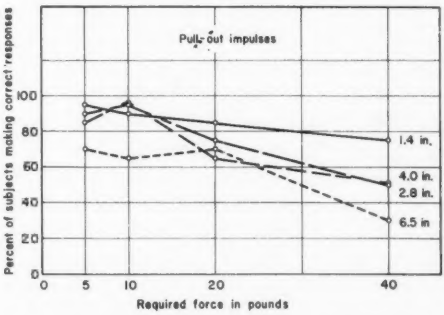

Fig. 4. Plot of the percentage of subjects making correct "pull-out" impulses as a function of the required force in pounds.

especially true for the 6.5-in. push-in distance. In Fig. 4, the tendency toward fewer correct responses with increased force requirements for the pull-out impulses seems to be greater than that indicated in Fig. 3.

In general, the shape of the impulse delivered when the subject was tractionless was approximately saw-toothed, with a somewhat rounded rise, followed by an abrupt fall to the baseline. A representative impulse is shown in Fig. 5. Under frictional conditions on the other hand, the shape of the impulse tended to be much more rounded and of much longer duration

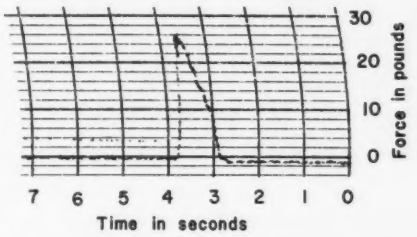

Fig. 5. A representative push-in impulse delivered under tractionless conditions.

for the same force-distance condition. A typical impulse for the frictional situation is shown in Fig. 6.

Because of the difficulty of obtaining an accurate measure of the area under the force-time records, and thus a value for the integral, $\int_0^t F dt$, the area was not used as one of the

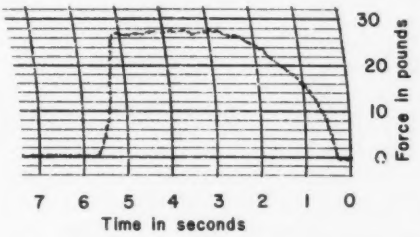

Fig. 6. A representative push-in impulse delivered under normal frictional conditions.

dependent variables of interest. Instead, the duration of the impulse was used as a first approximation of the area.

Fig. 7 shows the mean durations in seconds of the successful push-in impulses plotted against the required force in pounds. Fig. 8 shows the same values for the "pull-out" situation. It can be seen in Fig. 7 that there is a consistent decrease in duration of push as a function of increased nominal required force. This tendency is not as regular for the pull-out impulses shown in Fig. 8. The mean duration of the pull-out impulses for the 1.4-in. travel is approximately constant for all required forces. The Sign test[3] applied to the data

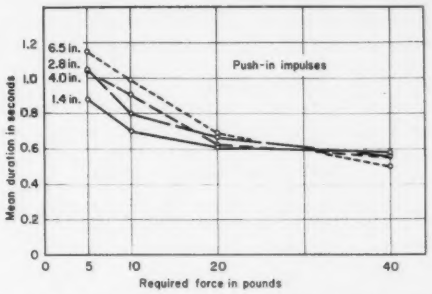

Fig. 7. Plot of mean duration of push-in impulses as a function of the required force in pounds.

of Figs. 7 and 8 shows that a statistically significant difference exists between the two types of impulses, since all the data prints of the push-in impulses are above all the pull-out points.

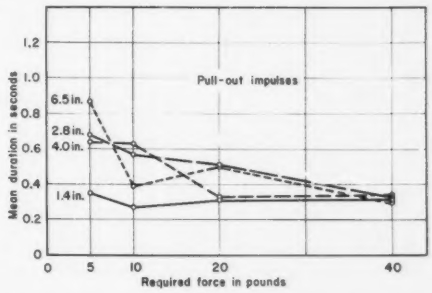

Fig. 8. Plot of mean duration of pull-out impulses as a function of the required force in pounds.

Figs. 9 and 10 show the mean impulse durations plotted against length of travel of the plunger. In general, there is a systematic variation which depends on the required force. This relationship is not quite so regular for pull-out impulses as it is for push-in impulses. In Fig. 10, there is some crossing over of the data points from one force to another which does not occur in Fig. 8.

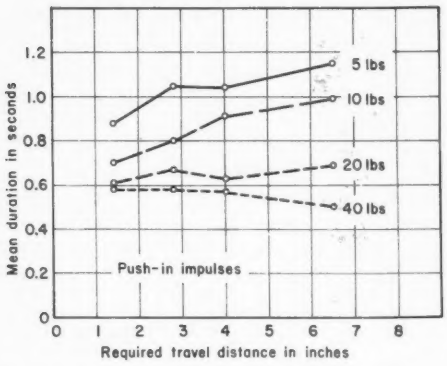

Fig. 9. Plot of mean duration of push-in impulses as a function of required travel distance.

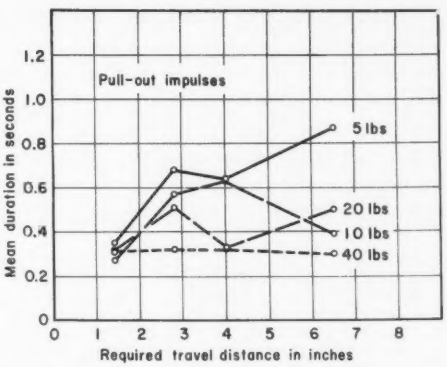

Fig. 10. Plot of mean duration of pull-out impulses as a function of required travel distance.

DISCUSSION

The applied impulses for the greater force and distance values were linear, with the handhold acting primarily as an anchor point. This linearity makes calculation of the impulse–momentum theorem, i.e. $\int_0^t F dt = mv_1 - mv_0$, easier than if the impulses were angular. In the latter case, the angular impulse–angular momemtum theorem, i.e. $\int_0^t T dt = Iw_1 - Iw_0$, would have had to be evaluated.

The area or successful value of the impulse may be approximated by three-fourths of the area of a rectangle whose base is the duration of the impulse, and whose height is the magnitude of the force applied or required. This study, however, was conducted with naïve subjects. It is possible that the wave form of trained subjects would differ. This possibility makes it valueless to attempt to specify with any greater accuracy, the exact impulse wave form.

By application of the Sign test,[3] it was shown that a statistically significant difference, at the 0.001 level of confidence, exists between the push-in and pull-out data which are shown in Figs. 3 and 4. In addition, except for the data points for the 1.4-in. push-in travel, there is a tendency at the 20 and 40 lb force requirements for push-in impulses to be more effective than pull-out impulses. The reason for this difference in the effectiveness of the push-in and pull-out techniques may be attributed to the position and role of the handhold. As mentioned earlier, the handhold served only as an axis about which the man revolved in reaction to his push impulse. For a pull, on the other hand, the subject was able to compensate partially for the forward motion caused by the reaction to the pull impulse by pushing against the handhold. Because of apparatus restrictions, furthermore, the distance that the subject was allowed to move as a result of the reaction to an impulse was quite different for pushes and pulls. For pulls, the distance was not more than about 2 ft. For pushes, however, it was about half the circumference of a circle of radius of approximately 2 ft, or a linear distance of about 6 ft.

The interesting technique, whereby a subject could bring himself to rest while still holding on to the object he had seated against a frictional force and without moving the object, can be explained by the following considerations. Essentially, the nonequivalence of equal impulses of different durations is demonstrated by this technique. If an applied force is to move an object against a frictional force, the applied force must exceed the frictional force. The subjects who used the technique did not allow the frictional force to be exceeded in their reaction motion. This was accomplished by suitable movements of the various arm and

shoulder muscles. It is thus possible to use a high-force, short-duration impulse to seat an object against friction, and yet remain anchored to the same piece of equipment by maintaining a longer duration force just below the frictional one. The long-duration impulse will be equivalent in terms of the action on the subject, but not of action on the piece of equipment.

It was interesting to see whether body weight in itself helped to perform the type of task investigated in this experiment. An inspection of the data for the 40 lb push and 6-in. travel showed no tendency for the heavier subjects to be more successful than lighter subjects. The median weight of the successful subjects was 175 lb in both the push-in and pull-out situations. This may be compared with the median weight for all the subjects which was 172.5 lb.

One point should be emphasized here. When dealing with a purely mechanical situation, it is possible to program linear forces and their durations so that a reciprocal relation exists over a wide range of values, i.e. the impulse is a constant. This is not possible, however, when dealing with an unanchored man and a manually applied linear force under tractionless conditions. The reasons for this are that (1) the arm by which the linear force is applied is limited in length, and (2) any force, no matter how small, will cause the unanchored man to move away from his point of application of the force. The effective duration when dealing with a 40-lb force is constant at approximately 0.3 sec, and is independent of the required distance of travel.

SUMMARY

1. When a man anchored by one handhold in a tractionless situation, applies a large-force impulse, he places himself directly behind the point of application of the force. This situation is linear and can be described by the impulse-momentum theorem.

2. The percentage of naïve subjects who give correct responses, i.e. push the plunger in or pull it out completely in one movement, falls as a function both of the required force, and of the required travel distance.

3. The shape of the graphic representation of the tractionless impulse is saw-toothed, with a rounded front and an abrupt fall. Its area can be approximated by taking three-fourths of the area of a rectangle whose base is the duration, and whose height is the force of the impulse.

4. For both push and pull impulses, the duration of the impulse falls as a function of an increase in the required force. Pull-out impulses are statistically and practically shorter than push-in impulses.

5. For this experiment, the maximum duration of an effective impulse for a required force of 40 lb, over all travel distances investigated, is 0.5 sec for a push-in impulse. For a pull-out impulse, it is 0.3 sec.

6. A man can seat a piece of equipment against a frictional force with a push impulse without the aid of any handhold and, in spite of the reaction to the impulse, remain attached to the equipment without unseating it. This is done by allowing the reaction to move the man over as long a distance as possible, and, since the total impulse is constant, reducing the force of the impulse. The reduction of the force in this manner does not allow the piece of equipment to be unseated because the force is now less than the frictional force required for seating.

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A Study of Visual Prediction Behavior[1]

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An experiment on prediction behavior was made using a visual tracking task. On four different trials, subjects viewed a simulated aircraft blip for varying lengths of time—3, 6, 12, and 24 sweeps of a simulated 5 rpm radar. After the viewing period, the blip was removed from the scope and the subjects were required to dead-reckon it for 10 min. A report of estimated range and azimuth was made once a minute. The major findings were: There was an increase in both range and azimuth error over the 10 min. dead-reckon period. The average error in azimuth was greater than the average error in range. There was a decrease in error from Trial 1 to Trial 2, but no improvement in performance after Trial 2. The length of the viewing period seems important only in its interaction with trials. For short periods of viewing only (three and six sweeps), there was improvement in estimation of azimuth position over trials.

Visual events in real life are seldom seen continuously. In a moving automobile, for example, pedestrians, signs, entrances to buildings, and other features of the visual world are seen to appear, disappear, and reappear. Although the observer is seldom aware of the fact, extrapolation from one such visual event to the next—from the disappearance to the reappearance of a particular object—is a common visual task. It seems likely that a number of factors influence the accuracy with which such extrapolations or predictions are made. Some of the more important of these are hypothesized to be the length of time which the object is viewed prior to its disappearance, the length of time during which the object or target is obliterated, the familiarity of the observer with the phenomenon, speed of motion, dependence or independence of the probabilities of the successive events, etc. Another factor influencing prediction behavior, which has been investigated by Gottsdanker [1–4] is the pattern of the track to be predicted.

The present study attempts to determine the accuracy of prediction behavior in a relatively simple situation in which the appearance time of a radar target prior to its disappearance is varied. The accuracy of prediction behavior is then checked continuously to determine the effect on prediction of longer and longer masking periods.

[1] The authors are now on the staff of the Thompson-Ramo-Wooldridge Corporation, DSL, Denver, Colorado.

METHOD

Subjects

The subjects were sixteen USAF airmen. All subjects were experienced radar scope operators assigned to the System Development Corporation in connection with other Air Force activities.

Apparatus

The radar display was a Plan Position Indicator (PPI). Targets appear on a PPI scope as points of light in a position determined by an azimuth (Q) and a distance from center, or range (R). A strobe of light, extending from the center of the scope face to the edge, sweeps around the circular face of the tube and blips are illuminated as the sweep passes the azimuth at which a target is located. In the present study, the entire 360° area was swept every 12 seconds or five times every minute. Targets were simulated utilizing equipment specifically designed and built for the purpose of target generation.

Two different tracks were used alternately on the successive trial sequences. One track originated at 45 degrees and 141 miles, the other track originated at 315 degrees and 141 miles. Both tracks moved due south tangent to the 100-mile range ring of the PPI scope. The scope was set at 200 miles maximum range. Targets moved at a constant speed of 600 knots.

Task and Instruction

Each subject was required to sit at a PPI scope and track a blip for a predetermined

period of time. These periods of time were expressed in terms of antenna sweeps: 24, 12, 6 and 3 sweeps. The antenna rotated at 5 rpm. Immediately following the predetermined number of sweeps, the blip was removed from the scope. The operators were then required to keep track of the position of the blip for a period of 10 min. At the end of each minute of the 10 min period a bell was rung to signal the operator to report the dead-reckoned position of the blip. Each subject reported range and azimuth each minute of the 10 min trial. Four ten min trials of a given track length (24, 12, 6 or 3 sweeps) were administered to each subject. There were four subjects per track length. Subjects reported over telephone lines to plotters standing behind small edge-lighted plexiglass boards. Plotters recorded the moves for subjects as reported without comment. Experimenters who monitored the lines between scope operators and plotters collected the data to be analyzed.

Prior to the start of the experiment, the following instructions were read to each subject:

"The experiment in which you are about to participate is a study of the ability of the human radar operator to predict the position of an aircraft after receiving a small amount of information about the course of that aircraft.

"You will be presented with an aircraft track on a PPI scope. After a fixed interval of time the aircraft will fade from the PPI scope. At one-minute intervals after the aircraft has faded you will be signaled with a buzzer. Each time the buzzer rings, you are to give a dead-reckoned range and azimuth position for the aircraft. After you have given ten such dead-reckoned positions, one session will be completed. You will then have a five-minute rest period, during which time you may smoke if you wish. After the rest period, we will start a second trial with ten more chances to DR targets. You will receive a total of four trials in all.

"You will be provided with a grease pencil and a scrub cloth for use at the scope both before and after the aircraft has faded. Do not attempt to correct a range and azimuth position which you have reported since the correction will not be accepted.

"Do you have any questions?"

The independent variables of the study were: (1) Track length (L) defined in terms of number of antenna sweeps. Four track lengths were used —24, 12, 6 and 3 antenna rotations. (2) Four trials (T) of a single track length were given to each subject. (3) Ten reports (R) within each trial were made by each subject.

Error Determination

The range and azimuth positions as reported by subjects were compared with the true range and azimuth of the blip at that time, and the error in range and the error in azimuth was calculated for each position reported by the subject. The true range and azimuth for the blip at each point in time were determined by direct readout from a special radar indicator (UPA–35).

RESULTS AND DISCUSSION

The results of the experiment were analyzed in terms of the discrepancy between subjects' estimates of the location of the target from minute to minute and the actual location as measured by the experimenters. Fig. 1 illustrates the increase of mean error in both range and azimuth as a function of time (reports) since target disappearance. An inspection of these figures reveals a difference of slope between the two curves. This difference appears to be a function of the fact that the true change in range of the target was not as marked from sweep to sweep as its change in azimuth. As Gottsdanker[1] has noted in the case of prediction motion, there is a tendency for subjects to tend toward the mean—adopting a more conservative approach to their estimates of the probable position of a target, and the present results are probably explainable in the same

terms. In the present study, the more conservative approach would favor range estimates because the differences in range from sweep to sweep were not as great as those in azimuth.

Mean range and azimuth error as a function of trials are plotted in Fig. 2. Obvious differences are apparent between the first trial and the last three, but the differences between trials two, three and four are not as marked.

Analyses of variance were performed on the range and azimuth errors obtained for the various lengths, trials, and reports. These are reported in Table 1 for azimuth and Table 2 for range. Both tables reveal similar trends. No significant effects are apparent due to subjects viewing the blips for different lengths of time prior to prediction behavior. In itself, this is a fact of considerable interest, because it means that when subjects had a very limited amount of information about the speed and direction of the target, further opportunity to view the blip did not lead to improved performance.

Trials in the present experiment involved repeated measurements on a subject following identical lengths of exposure to targets and, as a consequence, probably learning. This fact was pointed out with respect to Fig. 2, and both Tables 1 and 2 indicate that the variance due to trials is significant. When the interaction between trials and lengths is plotted (Figs. 3 and 4), it is obvious that the interpretation of these facts requires some qualification. The amount of error in range and azimuth depends upon the relationship of trials to length of viewing. In Fig. 3, for example, it can readily be seen that for subjects viewing the scopes for twenty-four sweeps prior to target disappearance, little if any change occurs from trial to trial, whereas

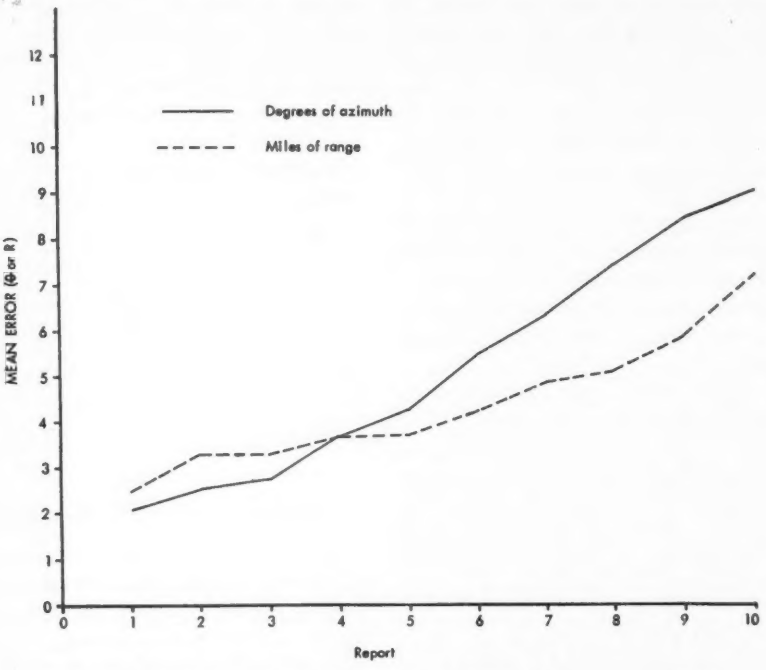

Fig. 1. Mean error in azimuth and range estimation for each of ten reports per trial.

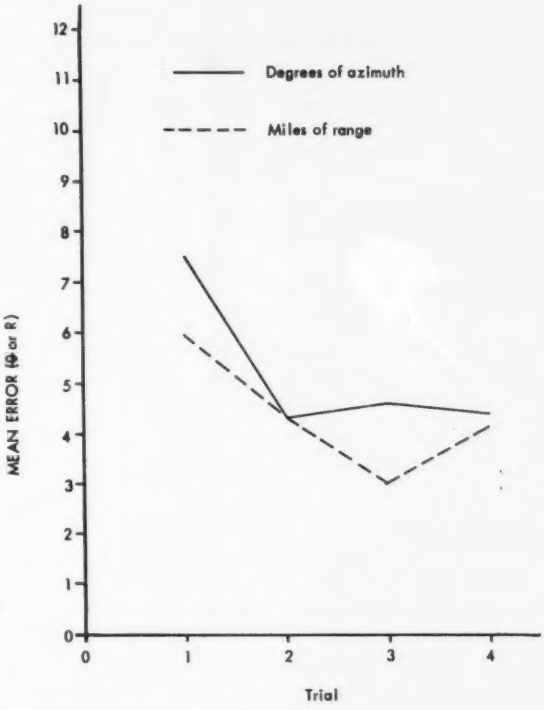

Fig. 2. Mean error in azimuth and range estimation for each of four trials.

TABLE I

Analysis of Variance of Errors in Azimuth Estimation

Source of variance	*d.f.*	*Mean square*	*F*	*P*
Total	639			
Between subjects	15	996.94		
Lengths	3	713.52	2.52	n.s.*
Error	12	283.42		
Within subjects	624	0.24		
Reports	9	417.87	19.51	<0.01
Trials	3	374.58	17.49	<0.01
$R \times T$	27	16.90	<1.0	n.s.
$L \times T$	9	156.32	7.30	<0.01
$L \times R$	27	17.64	<1.0	n.s.
$L \times R \times T$	81	8.52	<1.0	n.s.
Error	468	21.41		

* Not significant.

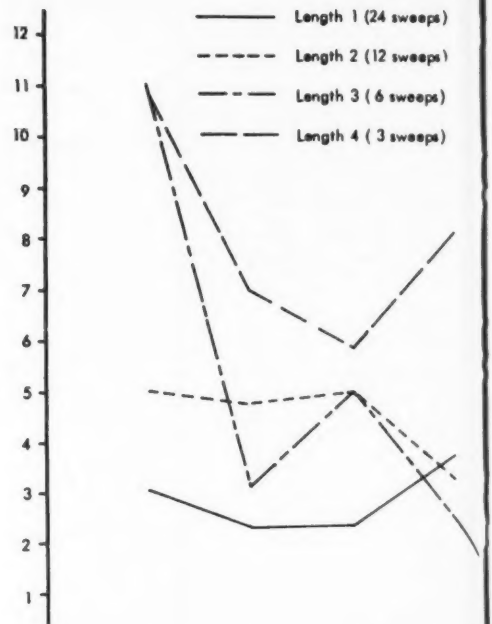

Fig. 3. Mean error of azimuth estimation, in degrees for the interaction of length of viewing and trial. Each line on the graph is a plot of mean error in miles for a different length of viewing the blip (number of radar sweeps).

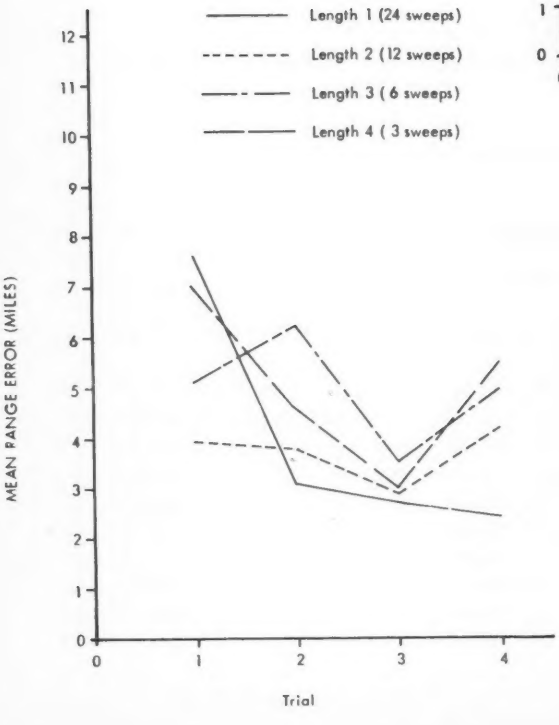

Fig. 4. Mean error of range estimation, in miles, for th interaction of length of viewing and trial. Ea line on the graph is a plot of viewing the bl (number of radar sweeps).

TABLE II

Analysis of Variance of Errors in Range Estimation

Source of variance	*d.f.*	*Mean square*	*F*	*P*
Total	639			
Between subjects	15			
Lengths	3	76.54	1.10	n.s.
Error	12	69.61		
Within subjects	624			
Reports	9	130.28	8.39	<0.01
Trials	3	227.12	14.63	<0.01
$R \times T$	27	9.82	<1.0	n.s.
$L \times T$	9	64.49	64.49	<0.01
$L \times R$	27	10.07	<1.0	n.s.
$L \times R \times T$	81	8.53	<1.0	n.s.
Error	468	15.53		

considerable change is evident for lengths of six and three sweeps. Apparently, subjects profited more from experience with these lengths of viewing than subjects receiving the opportunity for longer viewing. That is to say, there seems to be some minimal viewing time beyond which opportunity to view the blip does not result in improvement in performance. The results of the present study indicate that for the type of task employed, this minimal viewing time is between six and twelve sweeps of the radar, i.e. between 72 and 144 seconds.

Both Tables 1 and 2 show a significant variance in range and azimuth error due to reports. One aspect of the trend of these errors over reports was discussed earlier in connection with Fig. 1. From the two curves of Fig. 1, it can be seen that there is a gradual and consistent rise in error as the time since target disappearance increases. By the tenth minute, subjects show an average error of $7\frac{1}{2}$ miles in range and over 9° in azimuth. Depending on the distance of the target from the reference point, an error in estimate of 9° on the scope face may mean an error in real space of 25 or more miles; and for many purposes, such as the performance of a 90° beam intercept (where great accuracy is required), human prediction behavior is not sufficiently precise for the task.

There is little doubt but what the most elementary rate-aided tracking device would out-perform the human operator in making predictions of the type required by this experiment. Unfortunately, however, real-life predictions are seldom of the linear variety demanded here. Consequently, these results should not be interpreted to mean that prediction behavior in general can be done best by programmed automatic devices.

SUMMARY

An experiment on prediction behavior was made using a visual tracking task. On four different trials, subjects viewed a simulated aircraft blip for varying lengths of time—3, 6, 12 and 24 sweeps of a simulated radar turning at five revolutions per minute. After the stated viewing time, the blip was removed from the radar scope and the subjects required to dead-reckon the blip for 10 minutes. A report of the estimated range and azimuth of the blip was made once a minute. The major findings were: An increase in both range and azimuth error over the 10 minute dead-reckon period.

The average error in azimuth was greater than the average error in range. There was a decrease in error from Trial 1 to Trial 2, but no improvement in performance after Trial 2. The length of the viewing period seems important only in its interaction with trials. For short periods of viewing (three and six sweeps) the target, there was improvement in estimation of azimuth position over trials. For longer periods of viewing (twelve and twenty-four sweeps), there was no improvement in estimation of azimuth position over trials.

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